Marquette University
e-Publications@Marquette

Dissertations (2009 -)   Dissertations, Theses, and Professional Projects

Neuromuscular Function in Women Postpartum

Rita Deering
Marquette University

Recommended Citation

NEUROMUSCULAR FUNCTION IN WOMEN POSTPARTUM

by

Rita Deering, DPT

A Dissertation submitted to the Faculty of the Graduate School,
Marquette University,
in Partial Fulfillment of the Requirements for
the Degree of Doctor of Philosophy

Milwaukee, Wisconsin

August 2017

ABSTRACT
NEUROMUSCULAR FUNCTION IN WOMEN POSTPARTUM

Rita Deering, DPT

Marquette University, 2017

Efficient abdominal muscle function is important for functional mobility in men and women, and dysfunction of these muscles has been associated with impaired function such as low back pain. This dissertation explored abdominal muscle function in healthy young men and young women who have never been pregnant (nulligravid). As pregnancy and child birth also impact the tissues of the abdominal wall, this dissertation will also explore abdominal muscle function in postpartum women.

This dissertation involved three primary aims. *Aim1* compared abdominal muscle function and experimental pain perception in males and nulligravid females. Maximal strength over a range of trunk angles, force steadiness and fatigability of the trunk flexor muscles were assessed. Although the trunk flexor muscles of males were stronger than females, there were minimal differences in fatigability during an intermittent submaximal contraction. *Aim 2* determined the impact of pregnancy and childbirth on trunk flexor strength and fatigability at 8-10 weeks and 24-26 weeks postpartum. To determine the impact of delivery method, trunk flexor function was also compared in women who underwent Cesarean or vaginal delivery. Postpartum women were significantly weaker and more fatigable than control women up to 26 weeks postpartum. At 8-10 weeks postpartum, women who experienced Cesarean delivery were more fatigable than women who delivered vaginally, with no difference between delivery types at 26 weeks postpartum. Finally, *Aim 3* assessed a novel test of abdominal function that may be used in the clinic, and compared fatigability of the lumbopelvic stabilizing muscles and experimental pain in postpartum and nulligravid women, and across delivery types. The lumbopelvic stabilizing muscles of postpartum women were more fatigable than control women up to 26 weeks postpartum in the clinically adapted test. Postpartum women were also more sensitive to pain at the abdomen than control women at 8 weeks and 26 weeks after childbirth.

Thus, women had impaired abdominal function and increased pain at least 6 months after childbirth, with greater initial decrements in function after Cesarean delivery compared with vaginal delivery. These findings highlight the importance of assessment and rehabilitation of the abdominal muscles after pregnancy.

ACKNOWLEDGMENTS

Rita Deering, DPT

In no particular order, I would like to thank…

My parents and siblings, who have been an immense source of support, encouragement, and empowerment not only through this PhD journey, but throughout my life. I am the woman I am today because of their love, support, and guidance.

My husband, Ryan, for being one of my biggest cheerleaders throughout grad school! And for the sacrifices he has made to allow me to complete this dissertation.

My daughter, Mary, for giving me perspective and motivation! This journey would have been very different without her, and I was able to approach my research and data differently after experiencing motherhood firsthand. I hope that my work will benefit her if she decides to become a mother someday.

My in-laws, for the countless hours of babysitting and housework they offered, without complaint, so I could work on my dissertation or travel for conferences.

My adviser, Dr. Sandra Hunter, for allowing me to pursue a research topic that was close to my heart, but new to her laboratory; for being a true champion for this project; and for teaching me not only how to be an impactful researcher, but also how to be successful as a woman and a mother in science.

My committee (Dr. Marie Hoeger-Bement, Dr. Donald Neumann, Dr. Sarah Eickmeyer) for sharing their time, knowledge, and talents with me throughout this journey! Your input has been tremendously valuable and greatly appreciated!

My colleagues in the Hunter lab and peers in the CTRH program for their help with study design, data collection & analysis, manuscript writing, and overall moral support! I have made some wonderful friends and met impressive future independent researchers during my time at Marquette, and I look forward to following your careers!

The Women's Health Research Program at MCW for providing funding for the postpartum studies.

The American Association of University Women for providing funding to help my family and I cover daycare and other costs while I completed my dissertation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter IV. FATIGABILITY OF THE LUMBOPELVIC STABILIZING MUSCLES &
EXPERIMENTAL PAIN PERCEPTION IN WOMEN 8 & 26 WEEKS POSTPARTUM

I.   INTRODUCTION

Adequate function of the abdominal muscles is essential for several critical life

functions. The abdominal muscles and the fascia of the anterior abdominal wall provide

protection to the internal organs and blood vessels of the abdomen. The abdominal

muscles are also active as accessory muscles of ventilation during forced expiration and

during exercise. Several musculoskeletal impairments, such as low back pain and

incontinence, are also associated with inadequate abdominal muscle function.

Despite the importance of abdominal muscles for every day function, there is limited

understanding of how to best quantify abdominal function including muscle strength,

fatigability and control of force during postural and steady contractions. There are also

several variables that potentially impact the function of the abdominal muscles, including

sex of the individual, physical activity levels, and in women, the mechanical and

physiological changes that occur during pregnancy, and method of delivery experienced

during childbirth. This dissertation will explore the function of the abdominal muscles in

healthy young men and young women who have never been pregnant (nulligravid), as

well as the impact of pregnancy and mode of delivery where the abdominals and

surrounding fascia experience large and extended strains or trauma. Currently, there are

no clinical tools to assess fatigability of the lumbopelvic stabilizing muscles in patients

who have abdominal-related functional declines, disability and pain. The global aims of

the dissertation are to determine abdominal function in young men and women, and

understand the effects of pregnancy and delivery mode on abdominal function and pain in

women after childbirth, and pilot a clinical tool to assess fatigability of the abdominals in clinical populations such as postpartum women.

The following introduction will provide background to the anatomy and known function of the abdominal muscles, current methods of assessment of abdominal function, followed by general background on fatigability and control of force in men and women. Finally, the literature review will address what is known about the effects of pregnancy on abdominals and their function in women during and after childbirth.

Anatomy and function of the abdominal muscles

The abdominal muscles consist of the centrally located left and right rectus abdominis, the laterally located external oblique, internal oblique , and transversus abdominis (Neumann 2016). The rectus abdominis runs superior to inferior from the xyphoid process of the sternum and the cartilage of the 5th-7th ribs to the pubic bone. Right and left rectus abdominis are separated by the linea alba, a band of connective tissue/fascia that is formed by the common tendons of the external oblique, internal oblique, and transversus abdominis. The recuts abdominis muscles are also encased in the rectus sheaths, which are thick layers of fascia/connective tissue, also formed by the external oblique, internal oblique, and transversus abdominis, and consistent with the linea alba. The abdominal muscles (including rectus abdominis) are interconnected by a network of fascia and connective tissue, which allows force/stiffness generated by one muscle to be transferred to the other muscles and axial skeleton through the linea alba (Lee, Lee et al. 2008, Brown and McGill 2009).

The main functions of the abdominal muscles are: trunk flexion, posterior rotation of the pelvis, lateral trunk flexion, trunk rotation, control of intraabdominal pressure, protection of the abdominal internal organs, and stabilization of the lumbar spine and sacroiliac joint (Richardson, Snijders et al. 2002, Hodges, Kaigle Holm et al. 2003, Hides, Wong et al. 2007, Stokes, Gardner-Morse et al. 2011, Neumann 2016). Concentric contraction of bilateral rectus abdominis causes flexion of the trunk and/or a posterior tilt of the pelvis. The external obliques, which are the most superficial of the lateral abdominal muscles, have the largest cross sectional area and leverage of the abdominal muscles. The fibers of external oblique run in an oblique direction, from superior-lateral to inferior-medial ("hands in pockets"). Bilateral contraction of external obliques produces trunk flexion, while unilateral contraction produces trunk flexion combined with contralateral rotation. The internal obliques lie just deep to external obliques and have fibers that run perpendicular to external oblique. Bilateral contraction of internal oblique produces trunk flexion, while unilateral contraction produces trunk flexion combined with ipsilateral rotation. Both internal oblique and external oblique have fascial attachments, including the linea alba. The transverse abdominis however, differs in that its muscle fibers are horizontal to the ground during standing. Its primary role is to increase intra-abdominal pressure and to tension the thoracolumbar fascia, thus providing stability to the lumbar spine (Neumann 2016).

The abdominal muscles are also key muscles of forced expiration. At quiet rest, expiration is largely a passive process, achieved by relaxation of the diaphragm. During forced expiration, whether a volitional maximal exhale or during exercise when respiratory demand is increased, the abdominal muscles become active. By contracting

and increasing IAP, the abdominal muscles help to expel air from the thorax. The abdominal muscles also facilitate optimal inspiration by changing the position of the ribs and the abdominal contents, which places the diaphragm at an optimal length to produce the most force for the next inspiration (Neumann 2016).

Thus, bilateral rectus abdominis, external oblique, and internal oblique are the prime movers of trunk (thoracolumbar) flexion. The transversus abdominis does not contribute to trunk flexion, but is a primary muscle in the generation of intra-abdominal pressure and stabilization of the lumbar spine and sacroiliac joints. Given the critical nature of these muscles, it is important to understand muscular function for both trunk flexion and lumbopelvic stabilization tasks.

Role of the hip flexors in abdominal muscle function

The hip flexor muscles, especially iliopsoas and rectus femoris, are important synergists and antagonists of the abdominal muscles. When a muscle contracts, the freest segment will move, so stabilization of certain segments may be necessary in order to achieve the desired movement (Cort, Dickey et al. 2013). For example, the rectus abdominis can perform both thoracolumbar flexion and posterior tilt of the pelvis (Vera-Garcia, Moreside et al. 2011). The trunk has a much greater external moment than that of the pelvis, due to its length (moment arm) and bulk (Neumann 2016). So, an unopposed concentric contraction of the rectus abdominis is more likely to first produce posterior rotation of the pelvis rather than flexion of the thorax/trunk. The hip flexor muscles can cause hip flexion by moving the femur on the pelvis, or by anteriorly tilting the pelvis over a fixed femur. By opposing the posterior tilt of the pelvis, the hip flexor muscles

allow the abdominal muscles to perform thoracolumbar flexion. In a similar manner, the rectus abdominis contributes to stabilization of the pelvis to allow the hip flexors to perform femoral-on-pelvic hip flexion (Neumann 2016).

During a traditional full sit-up, both the abdominal muscles and the hip flexors are active. During the first phase of the sit-up, the trunk flexion phase, the abdominal muscles will flex the upper trunk by elevating the rib cage and scapulae off of the surface on which the person in lying (Andersson, Nilsson et al. 1997, Escamilla, Babb et al. 2006, Okubo, Kaneoka et al. 2010). The second phase, or hip flexion phase, is accomplished primarily by the hip flexors, which flex the superimposed trunk and pelvis about a fixed femur (Escamilla, Babb et al. 2006). The abdominal muscles are still active during this second phase, however, they do not contribute to the increased trunk/hip flexion; rather, they maintain the flexion of the upper trunk (Escamilla, Babb et al. 2006, Neumann 2016). Thus, when determining the roles of the abdominal muscles during a trunk flexion motion, the contribution of the hip flexor muscles can be significantly diminished by restricting the task to thoracolumbar flexion and limiting rotation about the hip.

Role of abdominal muscles & fascia in lumbopelvic stability

Appropriate transfer of loads through the lumbopelvic region is essential to nearly all functional mobility and performance of activities of daily living. Efficient coordination of the muscles of the trunk and lower extremity is necessary to achieve a balance of stability and mobility to allow successful task completion while minimizing adverse effects, such as joint hypermobility or organ prolapse (Lee, Lee et al. 2008).

During weight bearing, muscles oriented in the transverse plane, such as the transversus abdominis, the lower portions of internal oblique, the piriformis, and the pelvic floor muscles (especially coccygeus), are primarily responsible for stabilizing the sacroiliac joint (Richardson, Snijders et al. 2002, Hides, Wong et al. 2007). The abdominal muscles are active prior to upper and lower extremity movement in order to stabilize the trunk in preparation for these limb movements (Hodges and Richardson 1997, Urquhart, Hodges et al. 2005, Ericksson Crommert, Ekblom et al. 2011). Contraction of the transversus abdominis, internal obliques, and external obliques increases intraabdominal pressure, which increases stiffness of the lumbar spine and creates an extension moment at the lumbar spine, thus reducing the need for lumbar extensor muscle activity (Hodges, Kaigle Holm et al. 2003, Stokes, Gardner-Morse et al. 2011). The fascial network of the anterior abdominal wall has also been shown to be pivotal in the transfer of forces generated by the muscles to the spine and pelvis (Brown and McGill 2009).

Neuromuscular function: Assessment of abdominal muscle strength

Assessment of maximal strength is a common measure of muscular function (Kulig, Andrews et al. 1984, Neumann 2016). Strength of the abdominal muscles has been assessed in several ways. Dynamometers have been used in a variety of positions (sitting, standing, supine) and under varying conditions (isokinetic, isometric, etc) (Smidt, Herring et al. 1983, Nordin, Kahanovitz et al. 1987, Hall, Hetzler et al. 1992). Hall et al (1992) and Smidt et al (1983) have demonstrated that men produce 35% -57% greater isokinetic trunk flexion torque than women (Smidt, Herring et al. 1983, Hall, Hetzler et al. 1992) in seated dynamometer set-ups. Smidt et al (1983) also demonstrated

sex differences in isometric trunk flexion torque at four trunk angles, with men again demonstrating greater torque than women (Smidt, Herring et al. 1983). These studies, however, do not limit involvement of the hip flexor muscles, which may significantly contribute to trunk flexion torque.

Function of the transversus abdominis is frequently assessed by examining stability of the lumbar spine and pelvis. Hemingway et al (2003) used a pressure biofeedback unit under the lumbar spine and pelvis and assessed changes in cuff pressure while participants performed a drawing-in maneuver in supine with hips and knees flexed, and while performing a bent knee fall out (Hemingway, Herrington et al. 2003). The Active Straight Leg Raise test has also been used to assess the ability of the transverse abdominis to stabilize the lumbar spine and pelvis (Mens, Vleeming et al. 1999). This test involves the participant lying supine and raising one leg (fully extended) at a time. The participant subjectively rates the difficulty to raise the leg on a zero to five scale (zero = no difficulty, 5 = unable to raise leg). If difficulty is rated above a zero, a second trial is performed while manual compression is provided by the examiner to the participant's pelvis. If the task is easier with external manual compression, the test is considered positive and suggests instability of the pelvic joints. This test has been validated in several clinical groups, including pregnant and postpartum women, and is widely used clinically (Mens, Vleeming et al. 2001, Mens, Vleeming et al. 2002, Vleeming, Albert et al. 2008, Mens, in 't Veld et al. 2012). However, this test only assesses function of the transversus abdominis for a short period of time (5 second maximum), while many activities of daily living, such as carrying tasks, require submaximal activation of the transversus abdominis for several minutes. Thus, the

relevance to activities that require sustained activity of the transversus abdominis is not known.

In clinical situations, physicians and physical therapists use manual muscle testing (MMT) techniques to assess abdominal muscle strength by grading strength on a zero to five scale. One MMT method uses an abdominal curl-up, which requires clearance of the inferior angle of the scapula to be considered a successful trial, with varying positioning of the upper and lower extremities to adjust the difficulty of the maneuver. To achieve a grade of five, the individual must be able to clear the inferior angle of the scapula with the hands behind the head and the legs extended (without using the hip flexor muscles). A grade of four is assigned if the maneuver is successfully completed with the arms across the chest and the legs extended. A grade of three is assigned with the arms reaching toward the toes with the legs extended. For grades two and one, the legs are brought into a hook lying position (hips and knees flexed with feet flat). To achieve a grade of two, the curl up maneuver is performed with the arms outstretched toward the feet. For a grade of one, the participant needs to either be able to lift the head off of the testing surface or produce a forceful cough (Hislop and Montgomery 2002).

The Abdominal Muscle Test (AMT) is another method of MMT that focuses on the lumbopelvic stabilizing function of the abdominal muscles. The patient is positioned in supine with hips and knees bent and feet flat on the testing surface, with a pressure biofeedback unit beneath the lumbar spine. The patient is instructed to perform a posterior pelvic tilt, and to maintain that tilt while performing various lower extremity movements. Level 1 requires the patient to lift one leg and slowly lower as far as possible while maintaining pressure in the biofeedback unit. Level 2 requires the patient

to flex the hip of the stationary leg to 90°, and clasp their hands behind the thigh of the stationary leg, then raise the contralateral leg and lower it slowly as far as possible while maintaining pressure in the biofeedback unit. Level 3 is the same as Level 2, but support to the posterior thigh of the stationary leg is removed. Level 4 requires the patient to elevate both lower extremities and slowly lower them while maintaining pressure in the biofeedback unit. This test was validated in a group of young men and women with no history of low back pain (Gilleard and Brown 1994). However, only 18% of the participants in the validation study were able to successfully complete level 4 (Gilleard and Brown 1994). While these tests are useful as screening tools in clinical settings, where time and access to equipment may be limited, they lack sensitivity to discriminate the true force production capability of the abdominal muscles across individuals.

Neuromuscular function: Fatigability

Another important metric of muscle function is fatigability, which is also known as muscle fatigue. It is defined as an activity-induced decline in the maximal force or power of a muscle (Enoka and Duchateau 2008). Muscle fatigue begins shortly after onset of muscular activity, even if the muscle is still able to successfully meet the demands of a submaximal task (Hunter 2014). Fatigability has been shown to play an important role in motor performance, injury prevention, and rehabilitation (Enoka and Duchateau 2008).

Central fatigue occurs when mechanisms proximal to the neuromuscular junction are responsible for the decline in muscular performance (Gandevia 2001). These mechanisms may involve the motor nerve, the spinal cord, and/or supraspinal centers (motor cortex, deep brain structures, etc). Peripheral fatigue occurs distal to the

neuromuscular junction (Allen, Lamb et al. 2008). It can be caused by impaired cross-bridge cycling, excitation-contraction coupling (Ca^{2+} kinetics), depletion of metabolic substrates, and/or accumulation of metabolic byproducts (Allen, Lamb et al. 2008). Central fatigue can be quantified by stimulation of the motor cortex, motor nerve or muscle to obtain a value of voluntary activation. Central fatigue is the exercise induced reduction in voluntary activation (Merton 1954, Gandevia 2001). In order to obtain a measure of voluntary activation, stimulation is given during and after a maximal voluntary contraction (MVC). If an increase in force is elicited by the stimulation during a maximal voluntary contraction, it suggests that the nervous system is not fully driving the muscle (Merton 1954). If no increase in force is noted, then it is assumed that the muscle is maximally activated and any impairment in force is due to muscular mechanisms (peripheral fatigue). Decline in the electrically evoked resting twitch after the exercise as compared to before exercise would also indicate peripheral fatigue (Merton 1954). M-wave measurements can be used to assess neuromuscular propagation and thus rule out reductions in excitability of the neuromuscular junction as a cause of neuromuscular fatigue (Bigland-Ritchie, Jones et al. 1978, Bigland-Ritchie, Kukulka et al. 1982, Bigland-Ritchie, Furbush et al. 1986, Gandevia 2001, Enoka and Duchateau 2008).

Muscle fatigue is task dependent because changing the details of a task can alter the mechanisms and magnitude of fatigue. The cause of fatigue will depend on which site/factor is stressed the most (Hunter 2014). For example, when men and women were matched for strength and performed a sustained isometric contraction of the elbow flexor muscles, there was no sex difference in time-to-task failure (Hunter, Critchlow et al.

2004). However, when these same individuals performed an intermittent submaximal task with the elbow flexor muscles, women demonstrated a longer time-to-task failure than men (Hunter, Critchlow et al. 2004). This demonstrates that the type of task (sustained contractions vs intermittent contractions) was able to impact fatigability within the same muscle group.

Other examples of task dependency of muscle fatigue are shown when the contraction type and load compliance are altered. For example, old adults demonstrate a longer time-to-task failure with isometric contractions when compared to young individuals, but they have greater loss of power with fast dynamic contractions compared with young adults (Hunter, Critchlow et al. 2004, Hunter, Pereira et al. 2016). Here, the type of muscle contraction (isometric vs concentric) impacted fatigability and the differences between young and old adults. Constraints on the joint can also alter fatigability, as is evidenced by the force and position tasks. When an individual is asked to exert a given intensity of force against a rigid restraint (force task), time-to-task failure is usually longer (less fatigable) than maintaining a given joint angle (position task) while supporting an inertial load that is equivalent to the force produced in the force task (Hunter, Ryan et al. 2002).

Some other factors that will affect fatigability include the sex of an individual, their initial strength, and physical activity levels. In general, women are less fatigable (have a longer time-to-task failure) than men for isometric contractions and slow dynamic contractions (Hunter 2016, Hunter 2016). For sustained isometric tasks, this sex differences are in part mediated by strength. Men are generally stronger than women and when sustaining a contraction at the same relative intensity as women (Hunter 2014, Hunter 2016), muscle perfusion can differ as the larger muscles of men tend to exert

more pressure on the feed arteries, thus occluding blood flow and limiting muscular

performance at a faster rate than women (Hunter 2014, Hunter 2016). Sex differences in

time-to-task failure have been shown to disappear when external occlusion of blood flow

is employed during the contraction (Russ and Kent-Braun 2003). These findings are

supported by studies that have shown that the sex difference for sustained isometric

contractions disappears when men and women are matched for strength or when

covarying for strength (Hunter, Critchlow et al. 2004, Keller-Ross, Pereira et al. 2014).

During intermittent isometric contractions, however, women are less fatigable than men,

independent of strength (when matched for strength) or any possible differences in blood

flow (Hunter, Critchlow et al. 2004). With the intermittent isometric task, it is thought

that other mechanisms such as sex differences in fiber types, muscle metabolism and

sympathetic mediated vasodilation (Hunter 2014), results in less of a buildup of

metabolites and facilitate a more rapid perfusion and clearance of metabolites during the

rest period between contractions in the women compared with men. Women, in general,

have a greater proportion of type I muscle fibers than men (Hunter 2014, Hunter 2016).

As type 1 fibers are more fatigue resistant (Schiaffino and Reggiani 2011), this may

contribute to the longer time-to-task failure than men. Women also demonstrate different

metabolic substrate utilization than men. Women tend to oxidize more fat in response to

exercise, especially whole body exercise, than men, which results in a less rapid

accumulation of metabolic byproducts (Horton, Pagliassotti et al. 1998, Carter, Rennie et

al. 2001, Mittendorfer, Horowitz et al. 2002, Roepstorff, Steffensen et al. 2002,

Roepstorff, Thiele et al. 2006, Hunter 2014). More rapid accumulation of byproducts in

male muscle will alter the pH of the muscle more rapidly and may interfere with

excitation-contraction coupling. At the level of the sarcomere in the muscle fiber, women also tend to demonstrate slower Ca^{2+} ATPase activity and Ca^{2+} uptake in to the sarcoplasmic reticulum than men (Gollnick, Körge et al. 1991, Harmer, Ruell et al. 2014). These slower Ca^{2+} kinetics are associated with slower and more fatigue resistant fibers and, together, then result in women demonstrating slower relaxation rates and contractile properties, in general, than that for men (Hunter, Butler et al. 2006, Wust, Morse et al. 2008, Keller, Pruse et al. 2011). The sex differences in the contractile properties, muscle fiber types and metabolism will contribute to women being able to sustain intermittent contractions for a longer duration than men (Hunter 2014, Hunter 2016).

Physical activity and limb use may also impact fatigability. For example, after immobilization, both men and women showed a decline in force production but an increase in time-to-task failure, more so in the women than in the men (Cook, Kanaley et al. 2014). While this decline in fatigability (increase in time-to-task failure) was not expected, it may be due to strength-mediated mechanisms (improved blood flow due to less muscular pressure) and/or change in fiber type proportion during immobilization (loss or greater atrophy of type II fibers as compared with type I fibers) (Hunter 2014, Hunter 2016). Despite the importance of fatigability in muscular performance, fatigability is rarely assessed clinically and there are currently no clinical tests to assess fatigability of the abdominal muscles.

Assessment of abdominal muscle fatigability

Fatigability of the abdominal muscles has been assessed in laboratory settings with a number of modalities and conditions. Taylor et al (2006) examined the fatigability of the abdominal muscles in response to exhaustive cycling exercise by using magnetic stimulation and measurement of gastric pressure in young, healthy males (Taylor, How et al. 2006). Following cycling to exhaustion, the abdominal muscles experienced fatigue, as evidenced by reduced gastric pressure. Voluntary activation of the abdominal muscles and M-wave amplitude were not changed following exhaustive cycling, which suggests that peripheral mechanisms were responsible for the abdominal muscle fatigue (Taylor, How et al. 2006). As this study only examined males, it is unknown if sex differences exist in the fatigability of the abdominal muscles in response to exhaustive cycling.

Axial rotation of the trunk has also been used by several authors to examine abdominal fatigability. Ng et al (2003) studied 23 healthy young men (30.2 ± 7.9 years) and found that time-to-task failure for a sustained isometric axial rotation contraction at 80% of MVC was 45 ± 25 seconds for right rotation and 49 ± 21 seconds for left rotation. They also noted that the contributions of torques in the sagittal (flexion) and frontal (sidebending) planes decreased over time during the axial rotation fatiguing contraction, and that the variability of torque increased in all planes during the fatiguing contraction (Ng, Parnianpour et al. 2003). Another study of fatigability during isometric axial rotation found that men were able to maintain left isometric axial rotation at 60% MVC for 102 seconds while women had a time-to-task failure of 113 seconds for the same task (Kumar and Narayan 1998); however, the authors did not statistically analyze for sex

differences. Further study is needed to determine if sex differences in fatigability exist with trunk axial rotation contractions.

Fatigability during trunk flexion tasks has also been assessed. Smidt et al (1983) evaluated fatigability of the trunk flexors and extensors in sitting during a dynamic, reciprocal flexion/extension protocol through a range of motion spanning from 5 degrees short of maximal active trunk flexion to 10 degrees short of maximal active trunk extension. Participants performed maximal trunk flexion and extension contractions in the Iowa Trunk Dynamometer at 30 degrees/second until both flexion and extension peak torque declined by 25% of baseline values. This study found that the trunk flexor muscles were more fatigable than the trunk extensors, men were more fatigable than women, and individuals with low back pain were more fatigable than individuals without low back pain, regardless of sex (Smidt, Herring et al. 1983). In this study, men were also stronger than women, so the increased susceptibility to fatigue may have been mediated by strength, as has been shown in other muscle groups (Hunter 2016). This study also did not assess contribution of the hip flexor muscles to performance of the fatigue task.

Another commonly used test for measurement of both abdominal muscle strength and fatigability is the 1-minute sit up test. During this test, individuals perform as many sit ups as possible in one minute (Diener, Golding et al. 1995). While this test does provide evidence of abdominal muscle function, it is more a measurement of muscular power than of true muscular strength or endurance because the number of repetitions is recorded rather than failure of the force or power. The Georgia Tech cadence curl-up test was developed to address the issue of muscular power in the sit up test. It uses a metronome

to pace performance of curl-ups such that 25 curl-ups are completed in one minute. The test is performed for a maximum of three minutes, and has defined criteria for range of motion (elbows must contact the mid-thigh) and task failure (inability to complete full range of motion or to adhere to the cadence set by the metronome) (Sparling, Millard-Stafford et al. 1997). While this test is an improvement over the 1-minute sit up test in that it has defined criteria for failure, a fixed rate of contraction, and minimizes involvement of the rectus femoris muscles by fixing the feet on the wall, there were many subjects who did not reach task failure, which may mask any sex differences in fatigability.

Another clinically-accessible method of testing abdominal fatigability is maintaining a sit-up or curl-up position for as long as possible (McQuade, Turner et al. 1988, Moffroid 1997). Individuals with low back pain have been shown to be more fatigable when tested with a sustained sit-up or curl-up test. It has not been reported if sex differences are present in performance of these tests but, based on sex differences in other muscles, this should be considered. In addition, performance of a sustained sit-up or curl-up task to failure is sometimes reported as a measure of abdominal strength rather than fatigability (McQuade, Turner et al. 1988).

Given the importance of efficient abdominal muscle function for successful completion of activities of daily living, it is imperative to have a clear understanding of the fatigability of this muscle group. Several authors have demonstrated sex differences in fatigability for this muscle group for axial rotation and for trunk flexion when contribution of the hip flexors was not controlled. As such, we hypothesize that there will be sex differences in fatigability in that women will have a longer time to failure

when the contribution of the hip flexor muscles to a trunk flexion task is limited. It is

also unknown if sex differences exist in fatigability of the transversus abdominis as

assessed with a lumbopelvic stabilizing task. This dissertation will assess fatigability of

the trunk flexor muscles, limiting the contributions from the hip flexor muscles, and of

the lumbopelvic stabilizing muscles.

Neuromuscular function: Control of force (steadiness of contraction)

Steadiness is the ability to maintain a target force. When a "steady" contraction is

performed, the force does not stay static, rather, it fluctuates about a mean value (Enoka,

Christou et al. 2003). Steadiness can be quantified in absolute terms as the standard

deviation (SD) of force and in relative terms as the coefficient of variation (CV) of force

(Enoka, Christou et al. 2003). When the force of contraction increases, the SD of force

fluctuations will also increase. The CV of force allows comparison of steadiness, or

fluctuations, across varying intensities of contraction by normalizing the SD of force to

the mean force produced during the task; as such, CV is expressed as a percentage.

Sex, stress, age, and physical activity have been shown to impact control of force.

Generally, at low intensities, females exhibit greater force fluctuations than males. This

has been observed in the elbow flexors, first dorsal interosseous (finger abduction) and

knee extensor muscles (Christou, Jakobi et al. 2004, Clark, Collier et al. 2005, Brown,

Edwards et al. 2010), but it is not known if sex differences in force steadiness exist for

the trunk flexor muscles. Sex differences in steadiness have been reported when

cognitive stress is induced, with women demonstrating greater force fluctuations in

response to an acute stressor than men (Hunter 2014). Older adults tend to be less steady

during low intensity contractions than young individuals (Hunter, Pereira et al. 2016).

Practice of a skilled movement, strength training and participation in Tai Chi were all

shown to decrease force fluctuations, even when a change in strength was not noted

(Enoka, Christou et al. 2003).

 Several mechanisms can contribute to force steadiness.   In limb muscles, force

fluctuations are primarily explained by oscillations in common drive to the motor neuron

pool and the motor unit discharge rate variability (Enoka, Christou et al. 2003, Farina and

Negro 2015, Hunter, Pereira et al. 2016) resulting in larger force fluctuations at higher

contraction intensities when calculated as the SD of force. The force fluctuations

expressed as the CV, however, is reduced at the higher intensities of contraction, creating

an inverse relationship between force fluctuations and contraction force (Tracy 2007,

Tracy, Dinenno et al. 2007, Jesunathadas, Klass et al. 2012). Whether this relationship

between steadiness and contraction intensity is also present during trunk flexion

contractions is unknown, particularly given that activation of the motor neuron pool

occurs from multiple spinal levels during trunk flexion (Neumann 2016). Muscle co-

activation may also play a role in steadiness. Decreased force fluctuations are reported

during the position task, which also has greater co-activation of agonist-antagonist

muscles, suggesting that the co-activation helps to stabilize the contraction when

supporting an inertial load (Hunter 2014). Fiber type may also contribute to steadiness.

Muscle groups with a larger proportion of type I fibers (such as the ankle dorsiflexors)

demonstrate less force fluctuations than larger, more powerful muscle groups (Enoka,

Christou et al. 2003, Tracy 2007). Sex and age differences for muscles with larger

proportions of type I fibers are also less or non-existent, depending on the muscle group

(Enoka, Christou et al. 2003). Additionally, in limb muscles, force fluctuations will increase throughout a fatiguing contraction (Hunter and Enoka 2003, Hunter, Critchlow et al. 2004), and it is also unknown if this is true during fatiguing exercise of the trunk flexor muscles.

Given the important role of the abdominal muscles in regulation of intra-abdominal pressure and stiffness of the lumbar spine, an understanding of force control of this muscle group may be helpful in understanding postural stability and back pain. If significant fluctuations in force are observed, it is possible that subsequent fluctuations in IAP and lumbopelvic stability may also be present, which may contribute to the etiology of low back pain.

Relationship between abdominal muscle function and low back pain

Pain is defined as "an unpleasant sensory and emotional experience associated with actual or potential tissue damage" (Merskey, Bogduk et al. 1994). In response to localized trauma, peripheral sensitization can occur, where nociceptors in the affected area become more sensitive to stimuli. Prolonged experience of pain can lead to central sensitization, or alterations at the level of the brain and spinal cord that result in hypersensitivity to both noxious and non-noxious stimuli (Phillips and Clauw 2011). Quantitative sensory testing, such as measurement of pressure pain thresholds, can be used to identify alterations in pain perception and the mechanisms responsible for these alterations (Arendt-Nielsen and Yarnitsky 2009).

Approximately 30% of adults in the United States experience chronic pain (persisting for greater than 6 months) (Johannes, Le et al. 2010), and low back pain has been

identified as the leading cause of years lived with disability globally (Vos, Flaxman et al. 2012). Men typically demonstrate lower sensitivity to pressure pain stimuli (higher pressure pain thresholds) than women (Racine, Tousignant-Laflamme et al. 2012), and postpartum women frequently report low back and pelvic girdle pain (Ostgaard, Zetherström et al. 1994, Albert, Godskesen et al. 2000, Wu, Meijer et al. 2004, Parker and Millar 2008, Vleeming, Albert et al. 2008, Gutke, Lundberg et al. 2011). Exercise has also been shown to decrease pain sensitivity in healthy individuals and patient populations (Naugle, Fillingim et al. 2012). As such, it is important to understand the mechanisms that may contribute to low back pain in order to develop appropriate rehabilitation protocols to facilitate improved function, decreased pain, and decreased disability.

Several studies have identified impairments of the abdominal muscles in individuals with back pain. The transversus abdominis has been shown to demonstrate delayed firing in response to upper extremity movement in individuals with low back pain (Hodges and Richardson 1996). Elite cricketers with low back pain have demonstrated global activation of all abdominal muscles when attempting to activate only the transversus abdominis, resulting in impaired ability to perform a "draw in" maneuver (Hides, Stanton et al. 2008). Smidt et al (1983) found that individuals with low back pain demonstrated lower isometric and isokinetic trunk flexion torques, and were more susceptible to fatigue, than individuals without low back pain (Smidt, Herring et al. 1983). In postpartum women, increased inter-recti distance, suggesting compromised fascial integrity, has also been associated with low back and pelvic pain (Parker and Millar 2008).

Activation of the abdominal muscles to increase IAP has been shown to protect against low back pain by decreasing extensor muscle activity. The back extensor muscles produce greater torque than the abdominal muscles (trunk flexors) (El Ouaaid, Shirazi-Adl et al. 2013). Despite the abdominal muscles having greater leverage than the trunk extensors, the extensors have greater muscle mass and more of that mass consists of fibers that run vertically, thus giving the extensor muscles a greater advantage in producing sagittal plane torque. This greater torque of the extensor muscles produces greater compressive and shear forces on the spine, which may ultimately contribute to spinal injury (El Ouaaid, Shirazi-Adl et al. 2013). However, several authors have shown that increased IAP (generated by the abdominal muscles) produces an extension moment that decreases the amount of activity needed by the spinal extensor muscles, thus reducing the compressive and shear forces at the spine (Hodges, Kaigle Holm et al. 2003, Ericksson Crommert, Ekblom et al. 2011, El Ouaaid, Shirazi-Adl et al. 2013). Therefore, weakness of the abdominal muscles may decrease the extensor moment generated by abdominal muscle contraction, resulting in increased activation of the lumbar extensor muscles and increased spinal shear forces.

Low back pain and pelvic girdle pain are also common complaints during and after pregnancy (Ostgaard, Zetherström et al. 1994, Albert, Godskesen et al. 2000, Wu, Meijer et al. 2004, Parker and Millar 2008, Vleeming, Albert et al. 2008, Gutke, Lundberg et al. 2011). Other mechanisms may contribute to the generation and persistence of low back and pelvic girdle pain in this population.

Relationship between abdominal muscles and pelvic floor muscles

The abdominal muscles are also synergists with the pelvic floor muscles. Both the abdominal muscles and the pelvic floor muscles contribute to increasing/maintaining intra-abdominal pressure (Hodges and Richardson 1996, Sapsford, Hodges et al. 2001, Critchley 2002, Neumann and Gill 2002, Richardson, Snijders et al. 2002). The pelvic floor muscles also contribute to stability of the sacroiliac joints (O'Sullivan, Beales et al. 2002, Richardson, Snijders et al. 2002). Several studies have also shown co-activation of the pelvic floor and abdominal muscles (Sapsford and Hodges 2001, Sapsford, Hodges et al. 2001, Critchley 2002, Neumann and Gill 2002, Bo, Sherburn et al. 2003). In addition, in a study of women who were greater than 1 year postpartum (most of whom were post-menopausal), dysfunction of the abdominal muscles—specifically, increased inter-recti distance—was associated with disorders that are commonly attributed to dysfunction of the pelvic floor muscles, such as incontinence and pelvic organ prolapse (Spitznagle, Leong et al. 2007). There is also some evidence that surgical repair of deficits to the fascia of the anterior abdominal wall has led to resolution of urinary incontinence (Widgerow 1992, Smith, Smith et al. 1998, Mast 1999). These findings support that the abdominal muscles and the pelvic floor muscles act synergistically, and that dysfunction of one muscle group can contribute to impaired performance of the other muscle group.

Impact of pregnancy and childbirth on abdominal muscle function

Several physiological and lifestyle factors that occur during and after pregnancy can influence strength and fatigability of the abdominal muscles. These factors and their interactions are modelled in Figure 1.1 and discussed in this next section.

Figure 1.1. Model of Factors that Contribute to Strength & Fatigability of the Abdominal Muscles During & After Pregnancy
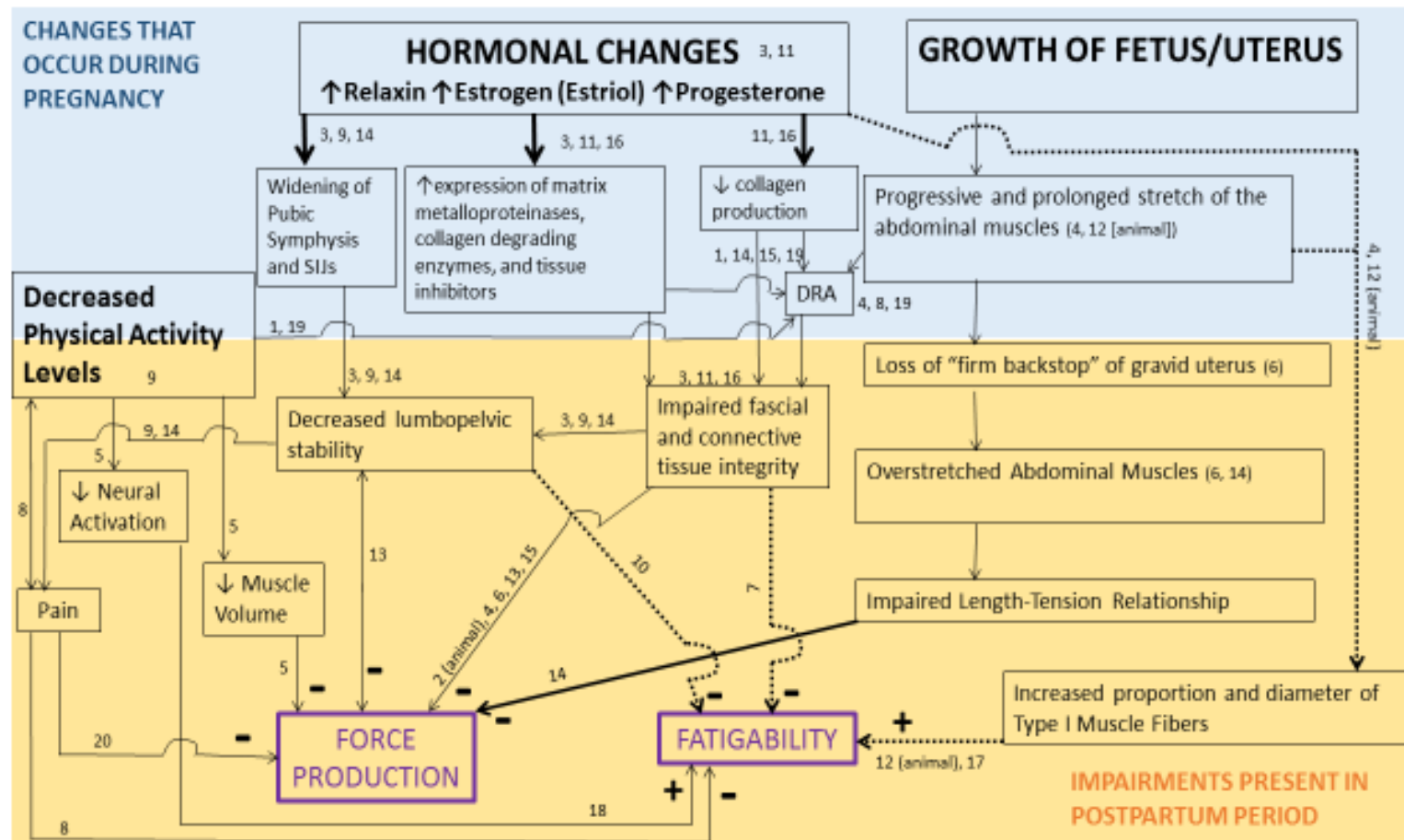
$^{1-20}$Citations listed in footnotes .

[1] Boissonnault & Blaschak 1988. [2] Brown & McGill 2009. [3] Chearskul 2006. [4] Coldron et al 2008. [5] Cook et al 2014. [6] Gilleard et al 2002. [7] Gracovetsky 2008. [8] Gutke et al 2011. [9] Gutke et al 2008. [10] Hunter et al 2002. [11] Kristianson et al 1999. [12] Lalatta Costerbosa et al 1988. [13] Lee et al 2008. [14] Lemos et al 2011. [15] Liaw et al 2011. [16] Negishi et al 2005. [17] Schiaffino & Reggiani 2011. [18] Semmler et al 2000. [19] Spitznagle et al 2007. [20] Thorstensson & Arvidson 1982.

The growth of the fetus and uterus requires expansion of the mother's abdominal cavity, resulting in progressive and prolonged stretch of the abdominal muscles (Lalatta Costerbosa, Barazzoni et al. 1988) which are maintained under tension by the gravid uterus. Animal studies have shown that the progressive stretch results in addition of sarcomeres in series (Lalatta Costerbosa, Barazzoni et al. 1988). After childbirth, the size of the uterus significantly decreases, but the muscles remain elongated, thus functionally putting the muscles on slack (Gilleard, Crosbie et al. 2002). It is possible that this increased length of the muscle will alter the length-tension relationship of the abdominal muscles and may cause "stretch weakness" of the abdominal muscles (Kendall, Kendall et al. 1952, Kendall and McCreary 1983). Animal studies have also shown that the stretch and the hormonal changes of pregnancy contribute to hypertrophy of Type I muscle fibers (Lalatta Costerbosa, Barazzoni et al. 1988), which suggests a shift to more oxidative metabolism and a less fatigable muscle (Schiaffino and Reggiani 2011). The degree of stretch is also a risk factor for Diastasis Recti Abdominis (DRA), or an increase in inter-recti distance (Boissonnault and Blaschak 1988, Spitznagle, Leong et al. 2007, Coldron, Stokes et al. 2008, Gutke, Lundberg et al. 2011).

Hormonal changes, including an increase in estrogen, progesterone, and relaxin, occur during pregnancy (Kristiansson, Svardsudd et al. 1999, Chearskul 2006). Relaxin, estrogen and progesterone affect connective tissue integrity by facilitating changes in collagen metabolism (Kristiansson, Svardsudd et al. 1999), causing a widening of the pubic symphysis and the sacroiliac joints, thus contributing to lumbopelvic instability during pregnancy, which may persist into the postpartum period (Chearskul 2006, Gutke,

Lundberg et al. 2011) and may contribute to lumbopelvic pain (Gutke, Ostgaard et al. 2008). Instability of the pelvic joints, which suggests an unstable anchor for the abdominal muscles, may contribute to increased fatigability in a manner similar to that of the position task in fatigability literature (Hunter, Ryan et al. 2002). Elevated relaxin levels during pregnancy increase the expression of enzymes that facilitate the breakdown of proteins involved in extracellular matrices, collagen and other tissues (Negishi, Li et al. 2005, Chearskul 2006), which leads to weakening of fascia and may contribute to development of DRA (Boissonnault and Blaschak 1988, Spitznagle, Leong et al. 2007, Liaw, Hsu et al. 2011). Fascia of the anterior abdominal wall has been shown to be critical in the transfer of muscularly generated force (Brown and McGill 2009), suggesting that DRA may impact force transfer from the abdominal muscles to the spine, pelvis and lower extremities. Gracovetsky et al (1977 &1983), in a study of the lumbodorsal fascia, showed that fascia also allows for redistribution of forces in a manner that prevents over-stressing one structure, possibly delaying the onset of fatigue in the trunk extensor muscles during carrying tasks (Gracovetsky, Farfan et al. 1977, Gracovetsky 2008). Thus, impairments in fascial integrity of the anterior abdominal wall may increase fatigability of the abdominal muscles during tasks that require postural stability.

Changes in physical activity levels may also impact muscle function in women during and after pregnancy. Sixty-eight percent of pregnant women report a decrease in physical activity during pregnancy and 80% of women report a significant decline in activity level postpartum (Gutke, Lundberg et al. 2011). Studies of muscular unloading/disuse have shown that females can experience significant declines in muscle volume and neural

activation with disuse, both of which lead to decreased force production, and, in some cases, decreased fatigability (Cook, Kanaley et al. 2014). Further, women who are not "regular exercisers" have greater risk of developing DRA and have worse abdominal muscle strength after pregnancy in comparison to women who are "regular exercisers" (Boissonnault and Blaschak 1988, Spitznagle, Leong et al. 2007).

Development of low back/pelvic girdle pain has been associated with abdominal muscle endurance and time-to-task failure on a back extensor test (Gutke, Lundberg et al. 2011). Pain can also lead to fear avoidance behaviors, which can decrease activity levels, furthering muscle weakness and thus perpetuating a cycle of weakness, instability, pain, and decreased movement (Gutke, Lundberg et al. 2011). Individuals with low back pain have also been shown to have lower isokinetic trunk flexion strength values than individuals without low back pain (Thorstensson and Arvidson 1982, Smidt, Herring et al. 1983).

Several musculoskeletal disorders, such as pelvic girdle pain and incontinence, have been linked to pregnancy and mode of delivery (vaginal vs Cesarean) (Wu, Meijer et al. 2004, Bastiaenen, de Bie et al. 2007, Spitznagle, Leong et al. 2007, Gutke, Ostgaard et al. 2008, Ronchetti, Vleeming et al. 2008, Vleeming, Albert et al. 2008, Robinson, Mengshoel et al. 2010, Vermani, Mittal et al. 2010). Despite the physiological changes that occur during and after pregnancy, and the musculoskeletal impairments that are commonly associated with pregnancy, the musculoskeletal system is not assessed as part of standard care during or after pregnancy (Borders 2006).

Does delivery method impact abdominal muscle function?

Vaginal delivery is directly associated with, and often the main risk factor for, pelvic floor dysfunction, including stress urinary incontinence, pelvic organ prolapse, and pain syndromes (Pool-Goudzwaard, Slieker ten Hove et al. 2005, Ashton-Miller and Delancey 2009, Prather, Dugan et al. 2009). As the abdominal muscles are synergists of the pelvic floor muscles (Sapsford, Hodges et al. 2001), and both muscle groups play a role in stabilization of the sacroiliac joints (Richardson, Jull et al. 1999, Richardson, Snijders et al. 2002, Hides, Wong et al. 2007), dysfunction of the pelvic floor muscles may create increased demand on the abdominal muscles for stabilization of the pelvic joints.

Almost a third of all births in the United States are via Cesarean section (Hamilton, Martin et al. 2015), which results in significant disruption of the fascial network surrounding the abdominal muscles, as the rectus muscles are separated to allow the child to be removed from the womb (Gilstrap III, Cunningham et al. 2002). Women who underwent a surgical delivery reported greater postpartum pain and a more arduous postpartum recovery than women who delivered vaginally (Lobel and DeLuca 2007, Declercq, Cunningham et al. 2008). Cesarean delivery has also been associated with higher maternal mortality and morbidity, greater risk for mood disorders following childbirth, and other negative psychosocial factors (Lobel and DeLuca 2007). Development of post-traumatic stress disorder (PTSD) as a result of childbirth has also been shown to be more strongly associated with delivery via emergency Cesarean section than vaginal birth (Ryding, Wijma et al. 1998, Söderquist, Wijma et al. 2002). PTSD is associated with increased fatigability and decreased force steadiness in men (Keller-Ross,

Schlinder-Delap et al. 2014); however, it is unknown how PTSD impacts fatigability and force steadiness in women, and especially in postpartum women. Despite the high number of Cesarean deliveries, and the potential impact on musculoskeletal function, there is minimal information on the recovery of muscle function postpartum in women who deliver via Cesarean section compared with vaginal birth. Thus, a major focus of the proposal is to determine if women who underwent Cesarean delivery will demonstrate greater impairments in abdominal muscle function, functional mobility and pain perception than those who experienced vaginal deliveries. We also sought to examine differences in abdominal muscle function between women who had experienced pregnancy and childbirth, and women who had never been pregnant.

Specific Aims

In order to better understand the impact of sex, pregnancy and mode of delivery on the function of the abdominal muscles, the studies in this dissertation quantified maximal trunk flexion torque across a range of trunk angles, fatigability of the trunk flexor muscles with an intermittent, isometric trunk flexion fatiguing protocol, and fatigability of the lumbopelvic stabilizing muscles with a novel clinical assessment. Experimental pain perception was also quantified. Because this protocol has not been established in the scholarly literature, and because sex differences in strength and fatigability have been identified in other muscle groups, we first tested our experimental protocol in healthy men and healthy women who had never been pregnant.

Aim 1: To determine if there are sex differences in abdominal muscle function.

Aim 1A: To compare maximal strength at different angles of trunk flexion, fatigability, and force steadiness of the abdominal muscles in healthy men and nulligravid women.

Aim 1A Hypothesis: Women will demonstrate a longer time-to-task failure, lower maximal torque, and a similar shape of the torque-angle curve compared with men.

Aim 1B: To compare experimental pain perception (pressure pain thresholds) at the nailbed and over the rectus abdominis muscle belly, and to assess the pain response to exercise in healthy men and nulligravid women.

Aim 1B Hypothesis: Women will demonstrate lower pressure-pain thresholds than men. Both men and women will demonstrate an increase in pressure pain threshold at the abdominal muscle testing site following fatiguing trunk flexor exercise. Minimal increase in pressure pain threshold is expected at the nailbed following fatiguing trunk flexor exercise.

Aim 2: To determine the impact of pregnancy and childbirth on <u>trunk flexor</u> strength and fatigability at 8-10 weeks and 24-26 weeks postpartum.

Aim 2A: To compare trunk flexor strength and fatigability in nulligravid and postpartum women at 8-10 weeks and 24-26 weeks postpartum.

Aim 2A Hypothesis: Postpartum women will have impaired abdominal muscle function (decreased strength, increased fatigability) in comparison to nulligravid women. Postpartum women will demonstrate an improvement in strength and

fatigability between 8 weeks and 26 weeks, but will continue to demonstrate deficits at 26 weeks compared with nulligravid women.

Aim 2B: To determine the impact of method of delivery (Cesarean vs vaginal) on abdominal muscle function at 8-10 weeks and 24-26 weeks postpartum

Aim 2B Hypothesis: Cesarean delivery will be associated with decreased strength and increased fatigability compared to vaginal birth, with greater difference between delivery types at 8 weeks postpartum.

Aim 2C: To determine the associations between physical function (functional mobility, physical activity levels, self-reported pain and disability) and abdominal muscle function in nulligravid and postpartum women.

Aim 2C Hypothesis: Individuals with lower abdominal muscle strength and greater abdominal muscle fatigability will demonstrate impaired physical function (shorter distance walked in six minutes, lower physical activity levels, greater self-reported pain and disability) than stronger and less fatigable individuals.

Aim 3: To assess the impact of pregnancy and childbirth on fatigability of the <u>lumbopelvic stabilizing muscles</u> experimental pain perception in nulligravid and postpartum women at 8-10 weeks and 24-26 weeks postpartum.

Aim 3A: To compare fatigability of the lumbopelvic stability muscles, with a novel test modified for clinical use, and experimental pain perception in nulligravid and postpartum women (8-10 weeks and 24-26 weeks postpartum).

Aim 3A Hypothesis: Postpartum women will demonstrate greater fatigability (shorter time-to-task failure) and heightened sensitivity to pain (lower pressure pain thresholds) at both time points as compared to nulligravid women.

Aim 3B: To determine the impact of method of delivery (Cesarean vs vaginal) on function of the lumbopelvic stabilizing muscles and experimental pain perception at 8-10 weeks and 24-26 weeks postpartum.

Aim 3B Hypothesis: Cesarean delivery will be associated with increased fatigability and heightened sensitivity to pain (lower pressure pain thresholds) compared to vaginal birth.

Aim 3C: To determine the association of the novel fatigue task of the lumbopelvic stabilizing muscles with clinical assessments of the abdominal muscles and with functional mobility.

Aim 3C Hypothesis: Women with greater fatigability of the lumbopelvic stabilizing muscles (shorter time-to-task failure) will demonstrate worse performance on clinical assessments of abdominal muscle function and impaired functional mobility compared to women who are less fatigable.

II.   SEX DIFFERENCES

IIA. Sex Differences in Trunk Flexor Strength & Fatigability

INTRODUCTION

Optimal function of the abdominal muscles is important for functional mobility, including lifting and carrying tasks (Lee, Lee et al. 2008). While the abdominal muscles are the prime movers of trunk flexion (Neumann 2016), this muscle group performs multiple other key functions. For example, the abdominal muscles, along with the diaphragm and pelvic floor muscles, regulate intra-abdominal pressure (IAP) (Hodges, Kaigle Holm et al. 2003). Through this regulation of IAP, the abdominal muscles also provide postural support and stability of the lumbar spine, while allowing transfer of loads from the extremities to the trunk (and vice versa) (Hodges and Richardson 1997, Hodges and Richardson 1997, Hodges, Kaigle Holm et al. 2003, Lee, Lee et al. 2008). The abdominal muscles also play a role in breathing and continence (Sapsford, Hodges et al. 2001, Neumann and Gill 2002, Lee, Lee et al. 2008, Sapsford, Richardson et al. 2008), through synergistic action with the diaphragm and pelvic floor muscles. The abdominal muscles are also isometrically active during movements of the upper and lower extremities (Hodges and Richardson 1997, Hodges and Richardson 1997, Hodges and Richardson 1999). Due to the need for abdominal muscle activation during nearly all functional tasks, these muscles are often active isometrically and at submaximal levels

during sustained contractions such as during a carrying task, or repetitive contractions, as during lifting tasks.

Given the importance of optimal abdominal muscle function and the lack of knowledge on the function of this muscle group, a more thorough understanding of the strength, fatigability and force control of these muscles is required. Sex differences in strength and fatigability have been identified in upper and lower limb muscles, with females typically demonstrating lower strength but decreased fatigability compared with males (Hunter 2014, Hunter 2016). Smidt et al (1983) showed decreased fatigability of the trunk flexor and extensor muscles in females during a maximal, reciprocal, dynamic fatiguing protocol; however, this study did not assess the contribution of the hip flexor muscles to the trunk flexion task (Smidt, Herring et al. 1983). Similarly, females were less fatigable in the back extensor muscles compared with males for a sustained submaximal isometric contraction at 50% maximal voluntary isometric contraction (MVC) (Clark, Manini et al. 2003). Intermittent isometric contractions of the abdominal muscles may be more functionally relevant, because postural stabilization is often achieved with isometric contractions, and many activities of daily living are repetitive in nature. Use of intermittent contractions also removes the confounding factor of the reduced blood flow experienced during sustained contractions. It is not known if there are sex differences in strength or fatigability for the trunk flexor muscles for a submaximal intermittent, isometric task.

An important aspect of force control that can affect functional performance is the steadiness of a contraction, which can be measured as the magnitude of force (or torque) fluctuations (Enoka, Christou et al. 2003, Almuklass, Price et al. 2016). During isometric

contractions of limb muscles, the fluctuations in force are quantified as the standard deviation (SD) about a target force of a sustained contraction, or as the coefficient of variation (CV) of torque when normalized to mean force produced (Enoka, Christou et al. 2003). In limb muscles, force fluctuations are primarily explained by oscillations in common drive to the motor neuron pool and the motor unit discharge rate variability (Enoka, Christou et al. 2003, Farina and Negro 2015, Hunter, Pereira et al. 2016) resulting in larger force fluctuations at higher contraction intensities when calculated as the SD of force. The force fluctuations expressed as the CV, however, is reduced at the higher intensities of contraction, creating an inverse relationship between force fluctuations and contraction force (Tracy 2007, Tracy, Dinenno et al. 2007, Jesunathadas, Klass et al. 2012). Whether this relationship between steadiness and contraction intensity is also present during trunk flexion contractions is unknown, particularly given that activation of the motor neuron pool occurs from multiple spinal levels during trunk flexion (Neumann 2016). In addition to input of common drive onto the motor neuron pool, other factors may influence the shape of this relationship for the abdominals. Additionally, in limb muscles, force fluctuations will increase throughout a fatiguing contraction (Hunter and Enoka 2003, Hunter, Critchlow et al. 2004), and it is also unknown if this is true during fatiguing exercise of the trunk flexor muscles in males and females. Generally, at low intensities, females exhibit greater force fluctuations than males. This has been observed in the elbow flexors, first dorsal interosseous (finger abduction) and knee extensor muscles (Christou, Jakobi et al. 2004, Clark, Collier et al. 2005, Brown, Edwards et al. 2010), but it is not known if sex differences in force steadiness exist for the trunk flexor muscles. A better understanding of the force control

of the abdominal muscles would be beneficial because the abdominal muscles play a major role in regulation of intraabdominal pressure and stiffness of the spine (Hodges, Kaigle Holm et al. 2003), so it is possible that large fluctuations in abdominal muscle force could cause fluctuations in IAP, thus impacting spinal stiffness.

This study determined if there were sex differences in isometric trunk flexion for MVC torque across a range of trunk flexion angles, fatigability, and torque steadiness in young, healthy males and females. We *hypothesized* that males would generate greater peak isometric trunk flexion torque because males typically have a greater muscle mass than females, especially in the upper body (Janssen, Heymsfield et al. 2000). Due to the critical role of the abdominal muscles in postural support and as accessory muscles of ventilation (Neumann 2016), we also hypothesized that, although females would be less fatigable than males, the sex differences would be small compared to those observed in limb muscles (e.g. elbow flexors) (Hunter and Enoka 2001, Hunter, Critchlow et al. 2004, Hunter 2016).

METHODS

Eighteen females (24.3 ± 4.8 years) and 15 males (24.1 ± 6.6 years) participated in two experimental sessions, separated by at least one day and no more than one week, to examine abdominal muscle function. All participants were healthy and free from cardiovascular disease, neurological impairment, chronic pain syndromes, and orthopedic conditions of the spine and lower extremities, and did not use any medications that impact neurotransmitters and/or neuromuscular excitability. Female participants reported they had never been pregnant. All participants provided written informed consent. The

protocol was approved by the Institutional Review Board at Marquette University, in accordance with the Declaration of Helsinki.

A dual x-ray absorptiometry (DXA) scan was performed during the first session to obtain estimates of lean body mass, fat mass, and bone mineral density of the whole body and specific regions using a GE Lunar iDXA (GE Healthcare, Little Chalfont, United Kingdom). Real-time ultrasound (GE Vivid e; 8 LRS linear probe) was used to assess thickness of the rectus abdominis muscles. Participants also completed a questionnaire to estimate physical activity (Kriska, Knowler et al. 1990). The physical activity questionnaire involved recall of occupational and leisure physical activity over the previous 12 months and each activity was weighted to estimate the metabolic cost of the activity (METs). Participants were provided with a list of 37 activities (with space for additional activities) and asked to provide frequency, quantity and intensity of activities over the previous 12-month period. METs were also able to be estimated for occupational physical activity based on occupational history and questions. Thus, the weekly metabolic equivalents (MET·hour·week^{-1}) was calculated from the occupational and leisure physical activity. Laboratory measurements of isometric trunk flexion MVC torque, submaximal torque steadiness and fatigability were made using a Biodex System 4 dynamometer (Biodex, Shirley, New York), as described below.

Trunk Flexion Torque

Participants were seated in a Back Flexion-Extension attachment for a Biodex dynamometer (Figure 2.1A) such that the right anterior superior iliac spine was aligned with the axis of rotation of the dynamometer. A scapular roll (15 cm diameter) was

positioned at the level of the scapular spine, and the head rest of the device was adjusted to participant comfort. The pelvis was stabilized with a sacral pad posteriorly and two tightly fastened straps anteriorly. A strap was also used to restrain the thighs. Vertical straps were placed on the anterior aspect of each shoulder to restrain the upper body, and these straps were joined at the midline of the chest with a buckle. Participants were instructed to flex their trunk, as though performing an abdominal curl-up, without allowing their legs to lift off from the seat. All trunk flexion attempts were visually assessed by the investigator (a physical therapist), and feedback was provided to participants if compensatory movement patterns were observed.

Trunk flexion torque was recorded online using a Power 1401 A-D converter and Spike2 software [Cambridge Electronics Design (CED), Cambridge, UK]. Torque signals were digitized at 500 Hz and displayed on a 48-cm monitor placed ~150 cm in front of the participant.

Electromyography

Electromyography (EMG) signals were obtained for the right rectus abdominis, left external oblique, and right rectus femoris using two 8-mm silver chloride surface recording electrodes (Coulbourn Instruments, Whitehall, PA) arranged in a bipolar configuration according to recommended placements (Cram 2011). EMG signals were amplified ($1000\times$) and band-pass (13-1000 Hz) and Notch (60 Hz) filtered with Coulbourn modules (Coulbourn Instruments, Allentown, PA). Signals were recorded online using a Power 1401 A-D converter (CED) and were digitized at 2000 Hz.

Experimental Protocol

All participants were instructed to refrain from caffeine for at least 2 hours and alcohol, pain medication, and anti-inflammatory medications for at least 12 hours prior to experimental sessions.

Session One

Body Composition. A DXA scan was performed to estimate fat mass, lean muscle mass and bone mineral density. Participants were asked to remove all metal before the scan. Participants were positioned on the scanner bed in supine with forearms in neutral position. Legs were bound just superior to the knees and the ankles with straps to prevent external rotation of the hips during the scan. Participants were asked to lie as still as possible and to not talk, unless there was a problem, during the scan.

Muscle Thickness. Ultrasonography was used to determine thickness of the right rectus abdominis muscle. Participants were positioned in supine on a plinth with their shirt removed. Muscle thickness measurements of the right rectus abdominis (Whittaker, Warner et al. 2013) were taken at 2.5 cm above and below the umbilicus. The full medial-lateral width of the rectus abdominis was scanned at each of these positions and the measurement was taken, while the participant held their breath at end expiration, in the region that visually appeared to be the thickest.

Torque-Angle Curve. To assess MVC torque at varying muscle lengths, and establish a torque-angle curve for the trunk flexor muscles, participants were placed in six different positions within the Back Flexion/Extension attachment (Biodex). A calibrated

digital angle gauge (Wixey WR300 Digital Angle Gauge, Barry Wixey Development, Sanibel, FL) was used inferior to the sternal notch to ensure that each participant was at the same position. Upright sitting was identified as zero degrees. MVC isometric torque was evaluated at 20 degrees of flexion, upright sitting, and 10, 20, 30, and 40 degrees of extension, in a randomized order.

Maximal Voluntary Contractions. Participants performed at least three isometric trunk flexion MVCs for ~3 s at each position. MVCs were separated by at least one minute of rest, in order to limit fatigability. MVCs were performed, with verbal encouragement, until the participant was able to perform two contractions where torques were within 5% of each other. The higher of these two contractions was used as the MVC. For each MVC, the participant was asked to flex the trunk forward, as though curling the shoulders down toward the hips without engaging the lower extremities. Participants were closely examined while performing trunk flexion MVCs in order to identify evidence of movements involving other muscle groups (e.g. legs elevating slightly off of chair due to activation of hip flexor muscles), and trials were only included in analysis if correct form was performed by the participant. On average, four MVCs were performed at each trunk angle, with a range of 3 to 6 MVCs for most participants. One participant did require 7 trials at one position, but was able to successfully perform the correct trunk flexion maneuver in 3-5 attempts for the remaining trunk angles. Participants were also cued to not hold their breath.

Although flexion of the upper trunk is primarily performed by the rectus abdominis muscles (Neumann 2016), EMG of the rectus femoris muscle in the lower limb was measured to provide quantifiable evidence that lower extremity muscles,

particularly those that contribute to hip flexion, were not being excessively utilized during the trunk flexion contractions. In order to normalize EMG of the rectus femoris during trunk flexion contractions, knee extension MVCs were performed to obtain maximal EMG. Three trials were performed at each position, with at least one minute rest in between each contraction. To perform MVCs of the knee extensors, an adjustable strap was placed around the shank of each participant to stabilize the limb.

Steadiness (Torque Fluctuations). Submaximal isometric contractions at five different intensities (5, 10, 20, 50, and 70% MVC) were performed among a subgroup of participants (9 females, 11 males) in order to assess torque fluctuations (steadiness). Participants were positioned upright (0º) and a computer monitor provided visual feedback of a target line at the respective trunk flexion torque. Participants were instructed to trace the line as steady as possible for six seconds. Two trials were performed at each intensity, with intensities performed in a random order.

Session Two

Intermittent Submaximal Fatiguing Protocol. Participants performed an intermittent isometric fatiguing protocol with the trunk flexor muscles in the upright position (0º), as many postural tasks are performed in upright positions, at an intensity of 50% MVC torque. Prior to the fatiguing exercise, participants performed baseline MVCs for trunk flexion and knee extension, as previously described. For the fatiguing exercise of the trunk flexor muscles, a target line representing 50% MVC was displayed on a computer screen in front of the participant. Vertical cursors were displayed to cue the participants when to contract (6 seconds) and when to relax (4 seconds). Participants

were instructed to trace the target line as accurately as possible during each separate

contraction. A trunk flexion MVC was performed every minute, and sustained for six

seconds, in order to match the contraction/relaxation cycle of the fatiguing task. Every

60 seconds participants verbally rated their perceived exertion during the 50% MVC

fatiguing task (modified Borg scale, 0-10 scale) (Borg 1982).

Each participant was verbally encouraged to continue the fatiguing task as long as

possible. Task failure was defined as inability to maintain target torque (50% MVC) for

3 of the 6 s of a contraction or an MVC $\leq$ 50% of baseline MVC. If task failure was

reached during a submaximal contraction, an MVC was performed as the next

contraction and then the fatiguing task was terminated. Representative torque and EMG

activity of a fatiguing exercise bout is shown in Figure 1B. To measure recovery, MVCs

of the trunk flexor muscles were performed 10 minutes and 20 minutes after the end of

the intermittent submaximal fatiguing protocol.

Figure 2.1. Experimental Set Up & Representative Data of Fatigue Task.

A
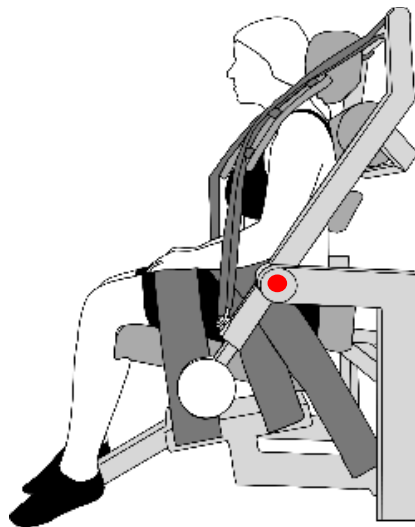
B
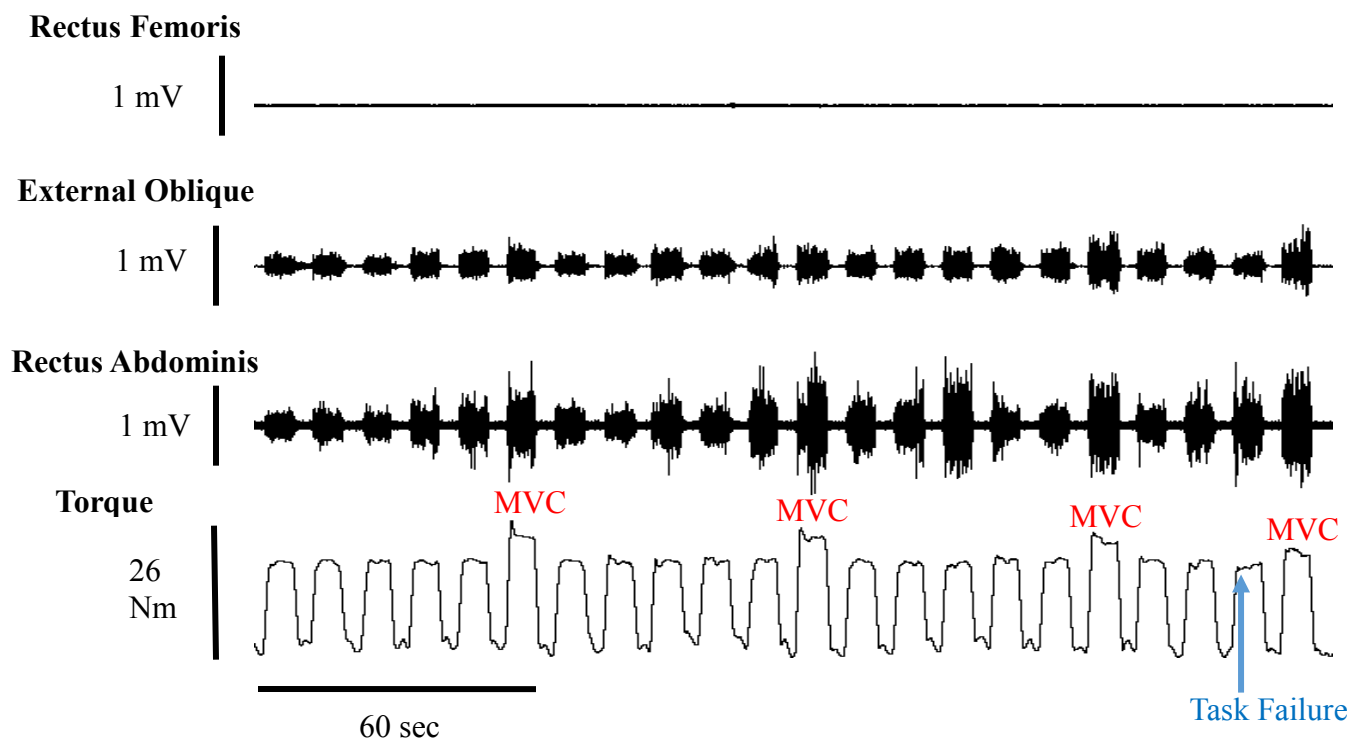
Figure 2.1. (A) Experimental set up of the Biodex Back Flexion/Extension attachment in the upright sitting (0°) position, used for the fatigue task. The frame of the attachment is represented in light gray, with padding in medium gray and restraints in dark gray. The red dot indicates the axis of rotation of the device. (B) Representative trace of raw data for a young male. EMG traces for right rectus femoris, left external oblique, and right rectus abdominis are shown. The bottom trace is trunk flexion torque and shows the 50% submaximal contractions with MVCs performed every minute starting at minute six for a 9.7-minute fatiguing exercise bout.

Data Analysis

Data obtained from the Biodex (MVC torque, steadiness of contraction, submaximal torque) was analyzed offline using Spike 2 software (CED). The MVC torque during trunk flexion contractions was determined by averaging the force over a 0.5 s interval around the peak torque during the MVC. Time-to-task failure for the

intermittent submaximal fatigue task was calculated from the onset of the first submaximal contraction to the end of the final MVC.

Torque steadiness was quantified as the standard deviation (SD) of torque during submaximal contractions and during the fatiguing protocol. Because the amplitude of the torque fluctuations is dependent on the absolute torque (Enoka, Christou et al. 2003), steadiness was also quantified as the coefficient of variation (CV) of torque, calculated as: (SD of torque/mean torque) $\times$ 100%. During the sets of submaximal isometric contractions (5, 10, 20, 50, and 70% MVC), torque steadiness was quantified over a three second interval of a six second contraction. In order to represent changes in the control of force during the intermittent submaximal fatigue task, torque steadiness was calculated as the average torque fluctuations from three submaximal contractions at each quartile of the exercise protocol (beginning, 25%, 50%, 75%, and 100% of time-to-task failure).

The maximal EMG activity of each muscle during trunk flexion MVCs was quantified as the Root Mean Square (RMS) value during the same 0.5 s interval as the MVC torque. During the intermittent submaximal fatigue task, EMG was quantified as the average RMS of the EMG signal from three submaximal contractions, and was obtained at the same intervals of the same submaximal contractions as torque and steadiness were calculated. MVCs for knee extension were also performed during each test session to obtain maximal EMG from the rectus femoris. Rectus abdominis and external oblique EMG during submaximal contractions was normalized to the RMS of the maximum EMG signal of each respective muscle obtained during trunk flexion MVCs in each test session. A 30 Hz high-pass filter was applied to rectus abdominis and external oblique EMG to remove ECG artifact (Redfern, Hughes et al. 1993). EMG of

rectus femoris during trunk flexion contractions (MVCs and submaximal contractions) was normalized to the RMS of the maximum EMG signal obtained from knee extension MVCs at each respective trunk position.

Ultrasound images were analyzed using the GE vivid e ultrasound machine. Thickness of the right rectus abdominis muscle was measured from the inferior aspect of the superior fascial border to the superior aspect of the inferior fascial border (Whittaker, Warner et al. 2013).

Statistical Analysis

Data within the text and tables are presented as means ± SD and in figures as means ± standard error of the mean (SEM). Independent samples t-tests were used to compare sex differences (males and females) for the following variables: subject characteristics, self-reported physical activity levels, rectus abdominis muscle thickness, MVC torque of trunk flexor muscles prior to fatiguing exercise, and time-to-task failure of the fatiguing task. Repeated measures analysis of variance (ANOVA) was used to compare across conditions with sex as a between subject factor for the following variables: torque steadiness (SD of torque and CV of torque) across time during fatiguing task and across intensities (% MVC) for submaximal contractions, MVC torque at each trunk position (torque-angle curve), and MVC torque from task failure through recovery. Pearson correlation was performed to determine the associations between dependent variables, with only significant correlations reported. Statistical analysis was performed on SPSS version 24 (IBM, Armonk, NY, USA). Significant differences were defined as $p \leq 0.05$.

RESULTS

Baseline Measures

Age, Body Mass Index (BMI), and physical activity levels were similar for males and females (Table 2.1). Males were taller (t_{31} = -3.7, p = 0.001), weighed more (t_{31} = -2.0, p = 0.049), and had lower body fat (t_{31} = 7.4, $p < 0.001$) than females. Males also had greater lean mass in the trunk (t_{31} = -6.4, $p < 0.001$) than females, even when trunk lean mass was normalized to height (t_{31} = -6.1, $p < 0.001$). Thickness of the right rectus abdominis muscle belly was 1.4 times greater in males than females when measured at 2.5 cm above the umbilicus (t_{31} = -3.48, p = 0.003), and 1.3 times thicker in males than females at 2.5 cm below the umbilicus (t_{31} = -3.7, p = 0.002). See Table 2.1.

Table 2.1. Subject Characteristics

		Females (n=18)	**Males (n=15)**
Age	years	24.3 ± 4.8	24.1 ± 6.6
Weight	kg	65.2 ± 12.6	73.1 ± 8.8*
Height	cm	166.6 ± 8.4	176.8 ± 7.6*
Body Mass Index	kg·m^{-2}	23.3 ± 3.5	23.1± 2.3
Body Fat	%	32.5 ± 5.1	18.6 ± 5.7*
Lean Mass in Trunk	kg	20.0 ± 3.6	27.0 ± 3.2*
Trunk Lean Mass/Height	kg/cm	0.12 ± 0.02	0.15 ± 0.02*
Self-reported physical activity over preceding 12 months (Data from 16 females and 14 males)	Met·hours·week^{-1}	44.7 ± 27.4	60.1 ± 39.9

Rectus Abdominis Muscle Thickness (*above umbilicus*)	cm	1.0 ± 0.18	1.4 ± 0.36*
Rectus Abdominis Muscle Thickness (*below umbilicus*)	cm	0.97 ± 0.13	1.3 ± 0.35*

kg=kilograms; cm= centimeters; m=meters; MET= Metabolic Equivalents; * indicates $p \le$ 0.05.

Torque-Angle Curve

Both males and females generated larger MVC torque in extended positions (-40°, -30°, -20°) relative to more flexed positions (-10°, 0°, 20°; position: $F_{5, 27} = 25.4$, $p < 0.001$, $\eta_p^2 = 0.825$; Figure 2.2). Pairwise comparison indicated all positions, with the exception of -30°, were statistically different ($p < 0.05$) than the position of peak torque (-40°). However, males had greater isometric torque than females (sex: $F_{1,31} = 7.5$, $p = 0.01$, $\eta_p^2 = 0.194$), but not for all positions (position × sex: $F_{2.4,} = 6.9$, $p = 0.001$, $\eta_p^2 = 0.182$). Post-hoc testing (t-tests with adjusted $\alpha < 0.025$) demonstrated sex differences in strength for the extended positions (-40°, $t_{31} = -3.0$, $p = 0.006$; -30°, $t_{31} = -3.2$, $p = 0.003$; -20°, $t_{31} = -2.5$, $p = 0.022$) with males generating greater torque than females in these positions. No sex differences in MVC strength were present in the -10°, 0°, and 20° positions.

Figure 2.2. Torque Angle Curve.
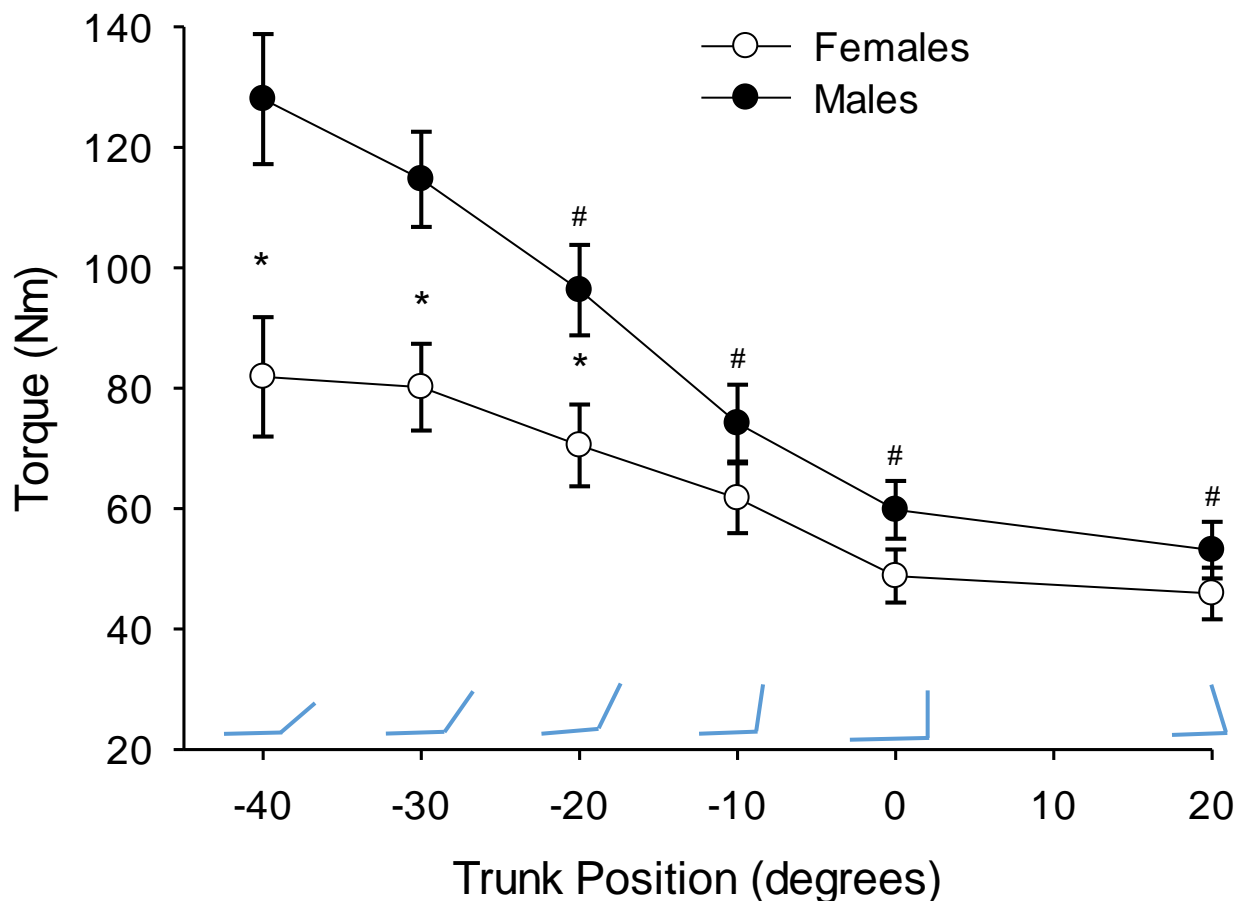
Figure 2.2. Maximal voluntary isometric torque of trunk flexor muscles at multiple sagittal plane trunk positions for males and females. * = sex difference in torque at this position. # = torque statistically different from position of peak torque.

EMG for torque-angle curve

EMG activity of the rectus femoris did not differ across trunk position (position: $F_{5, 27} = 1.6$, $p = 0.199$, $\eta_p^2 = 0.227$) and was not different between sexes (sex: $F_{1,31} = 1.0$, $p = 0.319$, $\eta_p^2 = 0.032$), suggesting that the differences in torque across positions was not a result of contributions from the hip flexor muscles.

Fluctuations in Torque (Steadiness)

Torque steadiness was quantified for contraction intensities ranging between 5% and 70% MVC in the upright sitting position (0º). Torque produced at each target intensity increased for both males and females (intensity: $F_{4,15} = 60.4$, $p < 0.001$, $\eta_p^2 = 0.941$; intensity × sex: $F_{4,15} = 1.2$, $p = 0.363$, $\eta_p^2 = 0.238$), with no difference in absolute or relative torque (% MVC) between the sexes (sex: $F_{1,18} = 2.4$, $p = 0.142$, $\eta_p^2 = 0.116$ and $F_{1,18} = 2.0$, $p = 0.205$, $\eta_p^2 = 0.087$, respectively).

Standard deviation of torque was greater at high intensities compared with low intensities (intensity: $F_{4,15} = 6.6$, $p = 0.003$, $\eta_p^2 = 0.639$), for both males and females (intensity × sex: $F_{4,15} = 1.3$, $p=0.299$, $\eta_p^2 = 0.264$; Figure 2.3).   CV of torque was highest at a target intensity of 5% MVC and declined as target torque increased (intensity: $F_{4, 15} = 21.4$, $p < 0.001$, $\eta_p^2 = 0.851$) for both males and females (intensity × sex: $F_{4, 15} = 2.5$, $p = 0.085$, $\eta_p^2 = 0.402$; Figure 2.3). There were no sex differences in SD or CV of torque (sex: $F_{1,18} = 0.339$, $p = 0.568$, $\eta_p^2 = 0.018$ and $F_{1,18} = 0.001$, $p = 0.977$, $\eta_p^2 < 0.001$, respectively).

Figure 2.3. Torque Steadiness of Trunk Flexion at Different Intensities of Contraction.
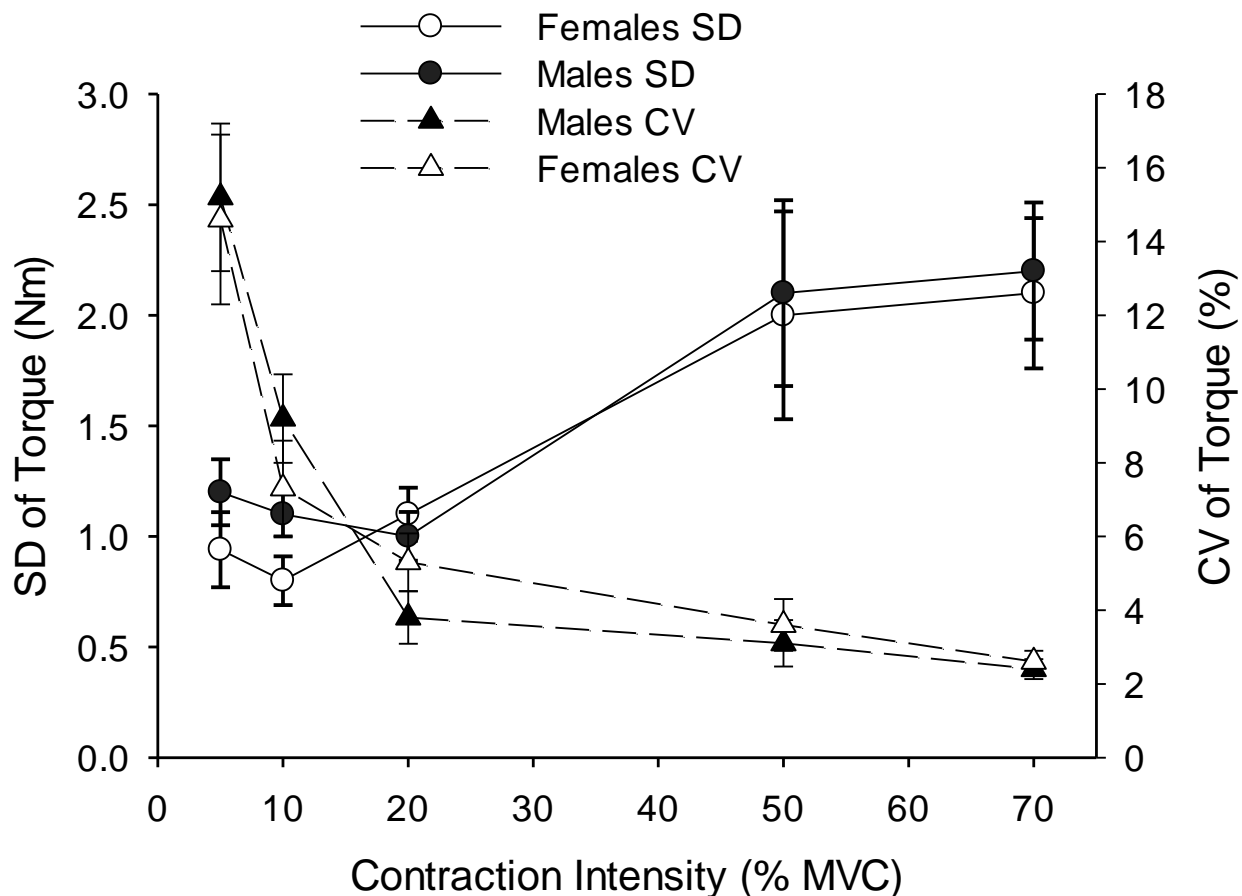
Figure 2.3. Mean (± SEM) torque fluctuations for males and females represented as the standard deviation (SD) of torque and the coefficient of variation (CV) of torque, at 5, 10, 20, 50, and 70% of maximal voluntary contraction (MVC) in upright sitting. Torque steadiness differed with contraction intensity for SD and CV but there were no differences between males and females.

Fatigability and Recovery

Time-to-Task Failure and MVC Torque. Time-to-task failure for the isometric intermittent fatigue task did not differ between males and females (sex: $t_{31} = -0.78$, $p = 0.440$; Table 2.2). MVC torque was not different between males and females at baseline (57.3 ± 23.8 vs 49.5 ± 22.2, respectively; $p = 0.336$) and declined during the fatiguing

exercise so that at task failure, the relative reduction in MVC torque from baseline was similar for the males and females (-30.64 ± 18.6% and -29.4 ± 13.7%, respectively; sex: $t_{31} = 0.18$, $p = 0.862$). MVC torque increased in recovery similarly for males and females (time × sex: $F_{2,30} = 0.6$, $p = 0.571$, $\eta_p^2 = 0.037$) with no difference between males and females (sex: $F_{1,31} = 1.1$, $p = 0.313$, $\eta_p^2 = 0.033$). By 20 minutes post exercise, MVC torque was fully recovered and similar between sexes ($t_{31} = 1.0$, $p = 0.315$; Table 2.2).

Table 2.2. Muscle Function and Fatigability Characteristics

		Females (n=18)	**Males (n=15)**
Baseline MVC at Zero position	Nm	49.5 ± 22.2	57.3 ± 23.8
Baseline MVC normalized to trunk lean mass/height from DXA	Nm/kg·cm^{-1}	1.6 ± 0.6	1.5 ± 0.7
Baseline MVC normalized to abdominal muscle thickness below umbilicus from US	Nm·cm^{-1}	51.0 ± 22.0	48.5 ± 20.3
Time to Task Failure	min	10.6 ± 5.5	12.4 ± 7.4
Rating of Perceived Exertion at task failure	0-10 scale	6.9 ± 2.0	6.0 ± 2.4
MVC at task failure	% baseline MVC	70.6 ± 13.7%	69.6 ± 18.6%
MVC at 10 min recovery	% baseline MVC	98.9 ± 23.7	90.5 ± 18.8
MVC at 20 min recovery	% baseline MVC	102.2 ± 18.7	94.2 ± 26.3

MVC=maximal voluntary contraction; US=ultrasound; DXA=dual x-ray absorptiometry; min=minutes; * indicates $p \leq 0.05$.

Torque and Steadiness during the Fatiguing Task. Average torque (Nm) and relative torque (% MVC) produced during the submaximal contractions was similar between the sexes (sex: $F_{1,31} = 0.58$, $p = 0.454$, $\eta_p^2 = 0.018$ and $F_{1,31} = 0.07$, $p = 0.797$, $\eta_p^2 = 0.002$, respectively) and declined over time (time: $F_{4,\,28} = 10.7$, $p < 0.001$, $\eta_p^2 = 0.604$ and $F_{4,\,28} = 12.4$, $p < 0.001$, $\eta_p^2 = 0.638$, respectively) for both males and females (time x sex: $F_{4,28} = 0.43$, $p = 0.789$, $\eta_p^2 = 0.057$ and $F_{4,28} = 0.72$, $p = 0.584$, $\eta_p^2 = 0.094$, respectively).

SD of torque increased during the fatiguing task (time: $F_{4,\,28} = 6.1$, $p = 0.001$, $\eta_p^2 = 0.467$) for both males and females (time $\times$ sex: $F_{4,\,28} = 0.64$, $p = 0.642$, $\eta_p^2 = 0.083$; Figure 2.4a). CV of torque also increased throughout the fatiguing protocol (time: $F_{4,\,28} = 6.4$, $p = 0.001$, $\eta_p^2 = 0.476$) for both males and females (time $\times$ sex: $F_{4,\,28} = 0.94$, $p = 0.456$, $\eta_p^2 = 0.118$; Figure 2.4b). There was no sex difference in force fluctuations when measured with SD or CV of torque (sex: $F_{1,31} = 2.0$, $p = 0.168$, $\eta_p^2 = 0.060$ and $F_{1,31} = 3.0$, $p = 0.094$, $\eta_p^2 = 0.088$, respectively).

Figure 2.4. **Steadiness of Submaximal Contractions During the Fatiguing Task.**
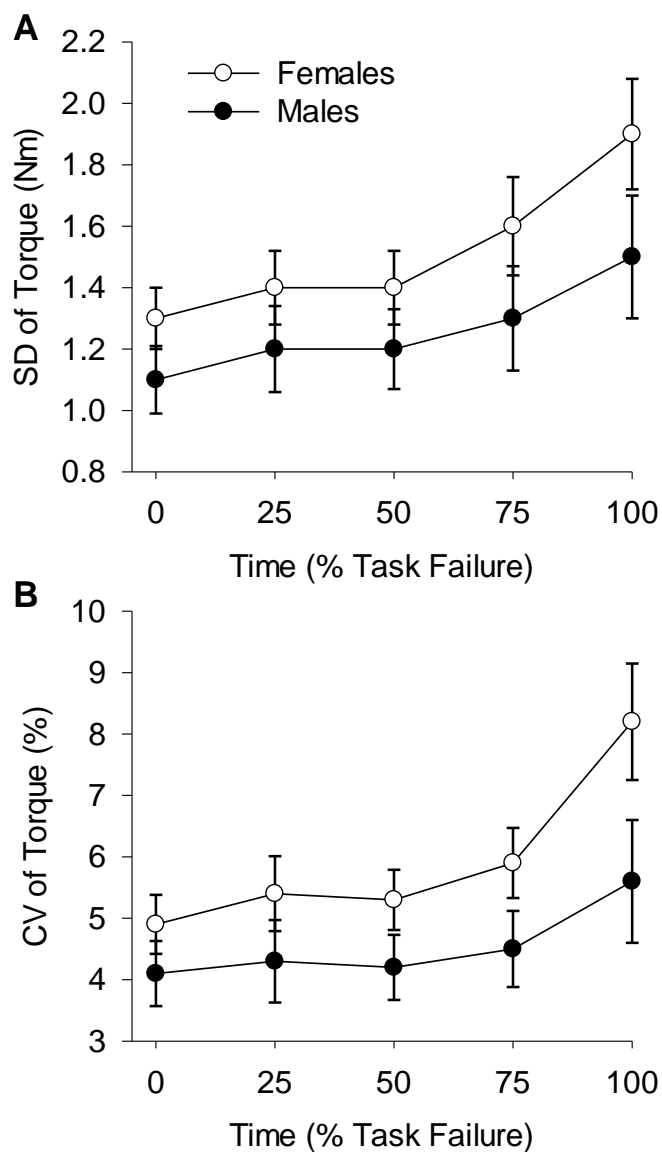
Figure 2.4. Steadiness of submaximal contractions performed during the intermittent isometric trunk flexion fatiguing protocol. Standard deviation (SD) of torque (A) and coefficient of variation (CV) of torque (B) are shown as the mean ± SEM of three submaximal contractions at each quartile (beginning, 25%, 50%, 75%, and end) of total time-to-task failure. Fluctuations in torque increase over time for both males and females (p<0.05) with no sex difference in steadiness between males and females.

EMG activity during the Fatiguing Task. EMG activity (% MVC) of the rectus abdominis (Figure 2.5) and external oblique muscles increased throughout the fatiguing protocol (time: $F_{4, 28} = 5.7$, $p = 0.002$, $\eta^2_p = 0.449$ and $F_{4, 28} = 5.9$, $p = 0.001$, $\eta^2_p = 0.457$, respectively), similarly for males and females (time × sex: $F_{4, 28} = 0.615$, $p = 0.432$, $\eta^2_p = 0.123$ and $F_{4, 28} = 0.615$, $p = 0.655$, $\eta^2_p = 0.081$, respectively). There was no sex difference of rectus abdominis or external oblique EMG activity during the fatigue task (sex: $F_{1,31} = 0.02$, $p = 0.899$, $\eta^2_p = 0.001$ and $F_{1,31} = 2.9$, $p = 0.096$, $\eta^2_p = 0.087$, respectively).

Rectus femoris EMG remained low (<12% of maximal EMG) throughout the fatiguing protocol for both males and females (time × sex: $F_{4, 28} = 1.6$, $p = 0.190$, $\eta^2_p = 0.191$), with no effect of time (time: $F_{4, 28} = 1.7$, $p = 0.175$, $\eta^2_p = 0.197$) or sex (sex: $F_{1,31} = 1.2$, $p = 0.275$, $\eta^2_p = 0.038$).

Figure 2.5. EMG of the Rectus Abdominis During the Fatiguing Task.
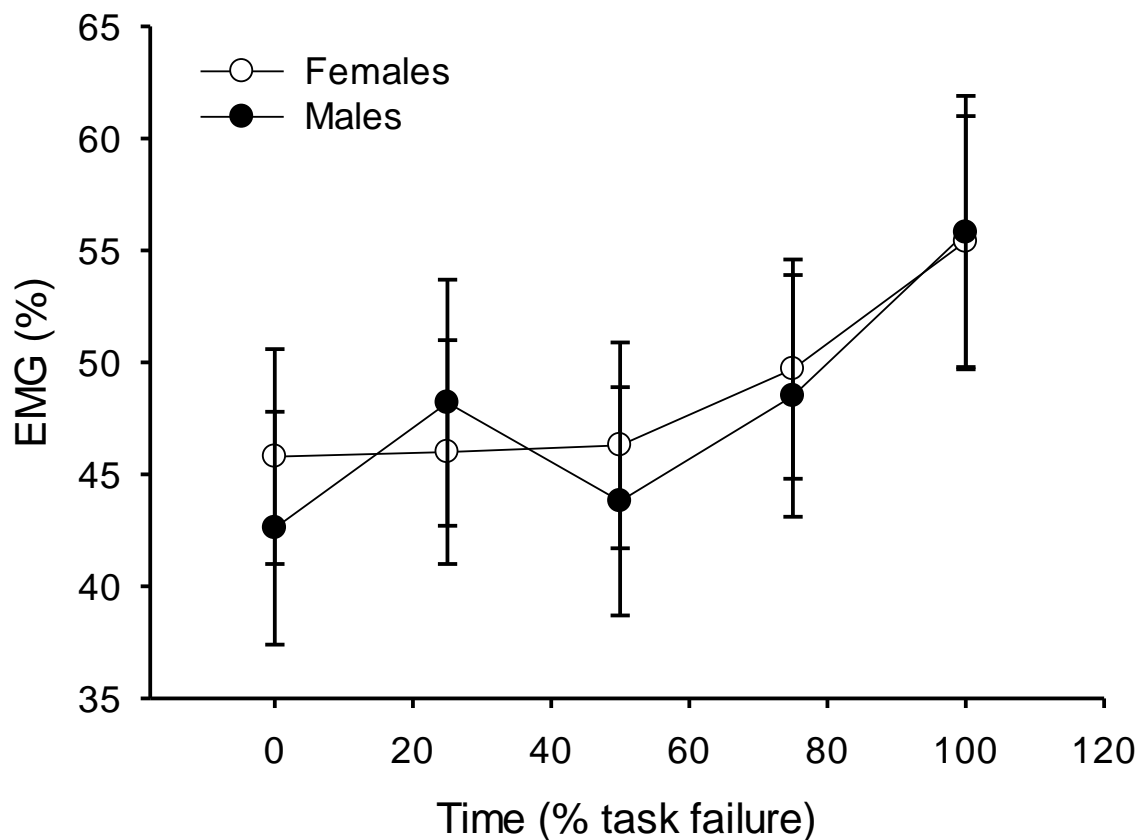
Figure 2.5. Mean (± SEM) RMS EMG (expressed as percent of maximal RMS EMG, %) of the Rectus Abdominis during submaximal trunk flexion contractions across the fatiguing protocol. Rectus Abdominis EMG increased over time ($p<0.05$) for both sexes ($p>0.05$) with no sex difference ($p>0.05$).

Associations between Variables

Trunk flexor MVC torque in upright sitting (0° trunk flexion) was positively, linearly correlated with fatigability of the trunk flexor muscles ($r = 0.473$, $r^2 = 0.223$, $p = 0.005$; Figure 2.6A). Trunk flexor MVC torque was also positively correlated with lean mass in the trunk, and this correlation was strongest at the -40° position, where both

sexes generated the greatest peak torque (-40°, $r = 0.595$, $r^2 = 0.354$, $p < 0.001$; 0°, $r = 0.378$, $r^2 = 0.143$, $p = 0.03$, Figure 2.6B). Longer time to failure of the trunk flexor muscles was associated with greater self-reported physical activity over the previous 12 months ($r = 0.456$, $r^2 = 0.208$, $p = 0.011$; Figure 2.6C). Greater self-reported physical activity over the previous 12 months was also associated with greater lean mass in the trunk ($r = 0.486$, $r^2 = 0.236$, $p = 0.007$; Figure 2.6D).

Figure 2.6. Associations
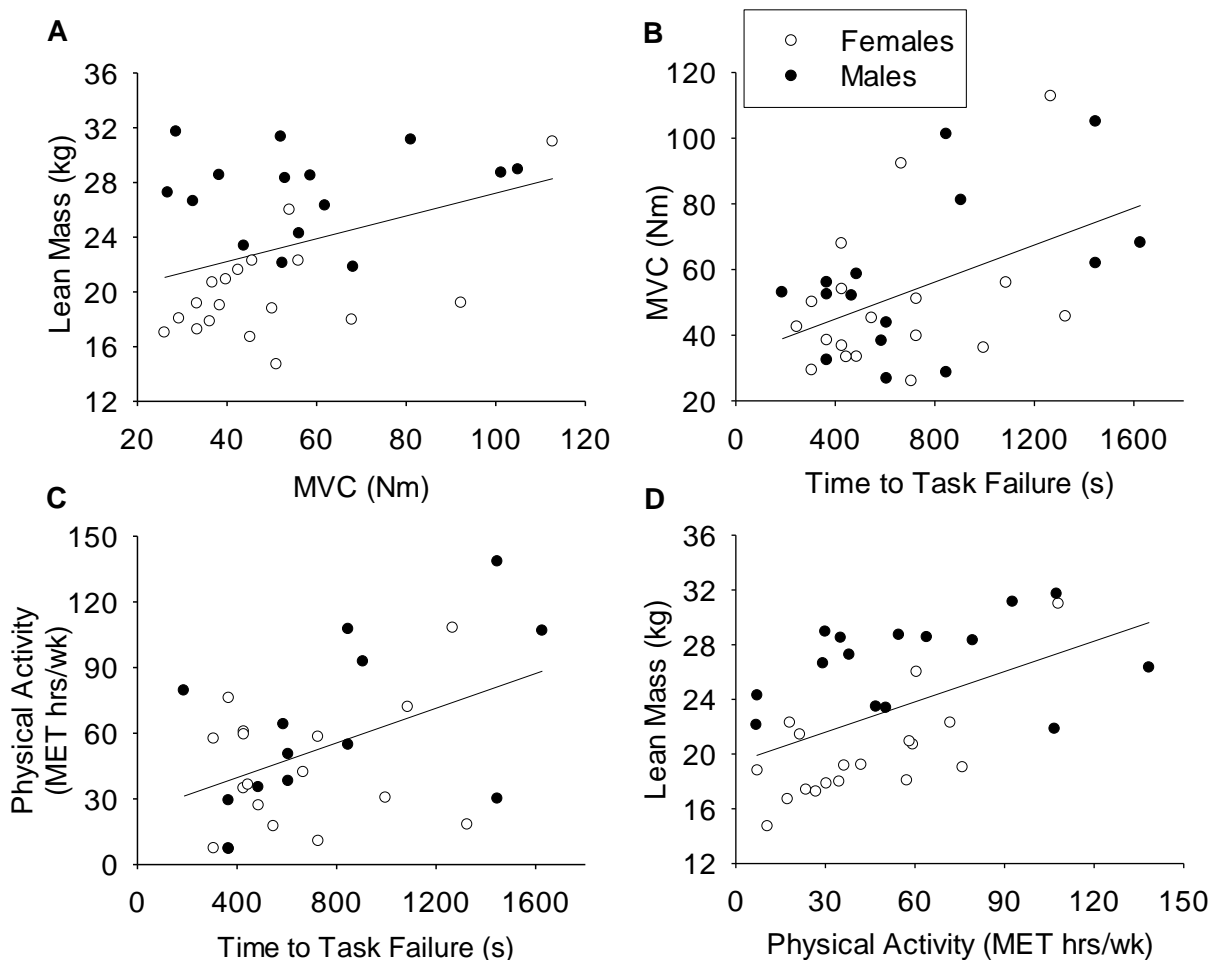
Figure 2.6 *A.* Greater MVC torque of trunk flexor muscles was associated with larger lean mass in the trunk (r=0.378, p= 0.011). *B.* Longer time to task failure during an intermittent isometric trunk flexion fatiguing exercise task was associated with greater MVC torque of trunk flexor muscles (r=0.473, p= 0.005). *C.* Longer time to task failure of the trunk flexor muscles was associated with self-reported physical activity levels over the preceding year (r=0.456, p= 0.030). *D.* Greater self-reported physical activity levels over the preceding year were associated with greater lean mass in the trunk (r=0.486, p=0.007).

DISCUSSION

There were several novel findings in this study. First, there was no sex-related difference in fatigability or steadiness of the trunk flexor muscles. Second, men were stronger than women (MVC torque), but this was only at the more extended positions. Accordingly, males had more lean mass than females (measured with DXA scan) and greater rectus abdominis muscle thickness (measured with ultrasonography). The strength of the relationship between lean mass and strength was strongest in the extended positions (-40, -30, -20), where a sex difference in strength was also observed. However, there was no sex difference in fatigability, or in strength in the upright and flexed positions (-10, 0, 20). Third, MVC torque and fatigability (time-to-task failure) of the trunk flexor muscles, both performed in upright sitting, were positively correlated, such that stronger individuals were less fatigable, and this is in contrast to several other muscle groups, such as the elbow flexor muscles (Hunter and Enoka 2001). Physical activity levels (self-reported) were associated with fatigability, demonstrating that more physically active people were less fatigable.

The relationship between torque steadiness and contraction intensity that we observed is consistent with that seen in other muscle groups such as the plantar flexors, dorsiflexors, finger abductors and elbow flexor muscles, such that the SD of torque increased and CV of torque decreased as contraction intensity increased (Tracy 2007, Jesunathadas, Klass et al. 2012). However, there was no sex difference in the torque steadiness during trunk flexion contractions while in upright sitting. For both sexes, however, the CV of torque of the trunk flexor muscles (15%), was higher than that

typically seen in other muscle groups at low contraction intensities (<10% MVC) (Figure 3), such as the first dorsal interosseous (~4%), elbow flexors (~2%), and quadriceps muscles (~1.5%) (Hunter, Critchlow et al. 2004, Tracy, Maluf et al. 2005, Welsh, Dinenno et al. 2007). As for other muscles, common drive to the motor units and their discharge rates of the trunk flexor muscles impact the steadiness of contraction (Farina and Negro 2015), probably explaining the similarity in the shape of the CV- force intensity curve between the abdominals and limb muscles.

There are several possible explanations for these muscle group differences in torque steadiness amplitude, i.e. the greater CV of torque of the trunk flexor muscles. First, the abdominal muscles are innervated from several spinal levels (T7-L1) (Neumann 2016). The activation of many alpha motor neurons from multiple spinal levels is required to control torque generated by the multiple large muscles that comprise the trunk flexors (Neumann 2016). The neurological complexity of this task may contribute to the large fluctuations in torque. The large CV of torque of the trunk flexor muscles may also be impacted by the relatively long and massive trunk, which may make this body segment more difficult to control than smaller limb segments, like the forearm or index finger. Ventilation may also impact torque steadiness, as the active abdominal muscles must accommodate the rhythmic expansion and contraction of the thorax and abdomen (trunk) during strength testing. This movement of the rib cage may also reduce the stability of the proximal attachments of the abdominal muscles (Hunter, Ryan et al. 2002). There may be minor contributions in the force output from chest and shoulder muscles, such as the upper trapezius muscles, because during the task the trunk was restrained by two large straps that contact the superior aspects of the shoulders. Lastly,

during contraction, the summation of forces from multiple motor units is influenced by the interaction between contractile tissue and connective tissue (Taylor, Christou et al. 2003). Thus, the presence of multiple tendinous intersections within the rectus abdominis (Neumann 2016), and the fascial attachments of the internal and external obliques, may impact the stability of the force generated by the muscle fibers and transferred across the connective tissue, possibly influencing the magnitude of the torque fluctuations during trunk flexion. The contribution of the mechanical and anatomical features of this unique muscle group, and the influence of discharge rate variability of the motor units from multiple muscles originating from common drive, is yet to be explored.

There was no sex-related difference in fatigability of the trunk flexor muscles for strength-matched males and females during the submaximal, intermittent isometric fatiguing protocol. This finding is in contrast to other muscles, such as the elbow flexors, where males demonstrated greater fatigability compared with strength-matched females (Hunter, Critchlow et al. 2004). The lack of sex difference in fatigability may be due to the fact that the abdominal muscles are a postural and ventilatory muscle group, and thus may be designed to be especially fatigue resistant in both sexes. Haggmark & Thorstensson (1979) showed that the abdominal muscles of males and females are comprised of approximately 55-58% type I muscle fibers, which are fatigue resistant relative to other fibers (type II) (Häggmark and Thorstensson 1979). In other muscle groups, females tend to have a greater proportion of type I muscle fibers than males, which may contribute to females being more fatigue resistant than males (Hunter 2014, Hunter 2016). However, in muscle groups that have a high proportion of type I fibers in both males and females, such as the tibialis anterior, the sex difference in fatigability is

diminished or absent (Avin and Law 2011, Hunter 2014), which is consistent with our findings. Furthermore, ratings of perceived exertion at task failure were not different between sexes in our study, suggesting that males and females gave similar effort during the fatiguing exercise task (Table 2.2). Ratings of perceived exertion at task failure were not, on average, at maximal levels, because some participants reported feeling as though they could continue the task if allowed to utilize compensatory movement strategies. However, all participants met the criteria for failure of the fatiguing task. Importantly, our study showed that physical activity was more a determinant of fatigability than the sex of the individual, as shown by the significant correlation between time-to-task failure and self-reported physical activity.

Strength and fatigability of the trunk flexor muscles were positively correlated. This is in contrast to most other muscle groups, where weaker individuals are more fatigue resistant, such as for sustained isometric contractions of the elbow flexor and hand grip muscles in young adults (Hunter and Enoka 2001, Hunter, Critchlow et al. 2004, Hunter, Schletty et al. 2006), where occlusion of blood flow is the primary mechanism responsible for the inverse relationship between strength and fatigability. The current study utilized an intermittent isometric protocol for which occlusion of blood flow is not a primary mechanism, thus making it less likely that strength-related blood flow differences between participants would influence fatigability. The role of the abdominal muscles in stability of the lumbar spine and pelvis, and as accessory muscles of ventilation (Neumann 2016), may explain the physiological need for a positive correlation between strength and fatigability in order to minimize injury risk and to avoid possible impairments with breathing during exercise. While these mechanisms were not

tested in this study, it is possible that some combination of neural input, muscle and connective tissue architecture (Gracovetsky 2008), blood flow (Manohar 1986), and sympathetic drive (Derchak, Sheel et al. 2002) may contribute to improved fatigue resistance with increasing strength.

The positive correlation between strength and fatigability in this study may provide insight into the lack of a sex difference in fatigability. Females are typically weaker than males and demonstrate greater resistance to fatigue but there was no sex difference in strength for the trunk flexor muscles in upright sitting, and this was the position for the test of fatigability. In strength matched males and females who performed an intermittent, isometric submaximal fatiguing protocol with the elbow flexors, also at 50% of MVC torque, women were less fatigable than men (Hunter, Critchlow et al. 2004). We did not observe this sex difference in fatigability of the trunk flexors in the males and females in this study, who did not differ in strength in upright sitting. While this study did not examine mechanisms responsible for fatigability, we hypothesize that several factors may contribute to the lack of a sex difference in fatigability. However, future research is needed to identify the mechanisms responsible for the relationship between strength and fatigability in this muscle group. This association also supports the importance of "core" strengthening.

Conclusion

This study shows that there are no sex differences in fatigability or force control during isometric trunk flexion contractions. These findings of minimal differences in fatigability for the trunk muscles is in contrast to other studies that show clear differences

in fatigability of other muscle groups, such as the elbow flexors and knee extensors (Hunter 2016). Furthermore, although men were stronger than females in the extended trunk positions of sitting, there was a minimal difference in maximal strength in upright and flexed sitting positions. Stronger males and females during upright sitting, however, were less fatigable than weaker individuals, and both strength and fatigability may be modulated by physical activity levels. The relationship between strength and fatigability of the trunk flexor muscles and physical activity supports the importance of abdominal muscle strengthening to offset fatigability.

IIB. Effect of Trunk Flexor Fatiguing Exercise on Pain Perception in Healthy Men

and Women

INTRODUCTION

The reduction in pain perception following exercise is known as exercise-induced hypoalgesia (EIH). The magnitude of EIH is dependent upon both the intensity and duration of exercise (Hoeger Bement, Dicapo et al. 2008, Naugle, Fillingim et al. 2012); greater pain relief occurs with fatiguing contractions (Hoeger Bement, Dicapo et al. 2008). Additionally, EIH may be larger at the exercising muscle than distal body sites (Kosek and Lundberg 2003, Vaegter, Handberg et al. 2014). Less is known about the importance of muscle specificity and the role of strength and muscle mass (Strasser, Draskovits et al. 2013). There is negligible data on the pain response to fatiguing exercise of the abdominal muscles. despite the frequent use of abdominal exercises in the treatment of a multitude of pain conditions (Wang, Zheng et al. 2012). The purpose of this study was to determine both local and systemic pain responses to abdominal muscle fatiguing exercise.

MATERIALS AND METHODS

Thirty-four adults (15 men, 24±7 years and 19 women, 24±5 years) performed an intermittent isometric fatiguing trunk flexion task. The protocol involved performance of trunk flexion contractions at 50% of maximal voluntary contraction (MVC) for 6 seconds with 4-seconds rest between contractions and 1 MVC every minute and at task failure

(Biodex Medical, Shirley, NY). Subjects were positioned in upright sitting that was verified with an angle meter.

Pain testing was performed before and after the exercise protocol in the Biodex apparatus. Pressure pain thresholds (PPTs) were assessed at the nailbed of the left middle finger and at the left upper rectus abdominis (5 cm above and 2 cm lateral to the umbilicus) using a computerized pressure algometer (Medoc Ltd, Yishai, Israel). Three trials were performed at each site with an inter-stimulus interval of 10 seconds at a rate of 10 kPa/s. Participants were instructed to press a timing device "as soon as pressure changes to pain." While testing the abdominal muscle site, participants received the same instructions with the added instruction to breathe normally and not to press their abdomen out against the algometer. Pain thresholds were recorded for all three trials and averaged.

Muscle thickness measurements of the right rectus abdominis were recorded at 2.5 cm above and below the umbilicus with a GE vivid e ultrasound machine (GE Healthcare, Little Chalfont, United Kingdom; 8LRS transducer). The full width of the rectus abdominis was scanned and the measurement was taken in the region that visually appeared to be the thickest at end expiration.

Change in PPTs were analyzed with repeated measures analysis of variance (ANOVA) over time (pre-post exercise) with sex as a between-subject factor, and independent t-tests compared subject characteristics and baseline PPTs between sexes. Correlation analysis between change in PPTs (post-pre) at the rectus abdominis muscle and muscle thickness was conducted with Spearman's rho nonparametric correlation due to non-normal distribution of ultrasound data. Pearson correlation was used to explore

the relationship between baseline pain and pain response to exercise at both the nailbed and the abdomen. Significance was identified at $p < 0.05$.

RESULTS

There was no sex difference in trunk flexion strength (MVC torque) in upright sitting, time to task failure for the intermittent isometric fatiguing protocol, or baseline PPTs at the abdominal muscle ($p > 0.05$). Men had greater muscle thickness while supine, greater trunk flexion strength while reclined ($p = 0.002$), and higher baseline PPTs at the nailbed ($p = 0.05$) than women.

Men and women demonstrated a similar increase in PPTs (i.e., similar EIH) at the rectus abdominis site after fatiguing exercise (time effect $p < 0.001$; time x sex $p > 0.05$; sex $p > 0.05$). Change in PPTs at the abdominal muscle site was positively correlated with muscle thickness ($r_s = 0.416$, $p = 0.014$). A trial by sex interaction ($p = 0.022$) was present for pain thresholds at the nail bed with fatiguing exercise: men demonstrated a decline in PPTs (i.e., hyperalgesia) at the nailbed following isometric trunk flexion fatiguing exercise (318 kPa pre-exercise vs 288 kPa post-exercise, $p = 0.021$), and women had no change in PPTs (226 kPa pre-exercise vs 228 kPa post-exercise, $p = 0.732$). Baseline PPTs at the nailbed were also associated with the change in PPT after exercise ($r = -0.425$, $p = 0.010$), but baseline PPTs at the abdomen were not associated with EIH at the abdomen ($r = -0.028$, $p = 0.872$).

Figure 2.7. Change in PPT at the Nailbed in Response to Trunk Flexion Exercise
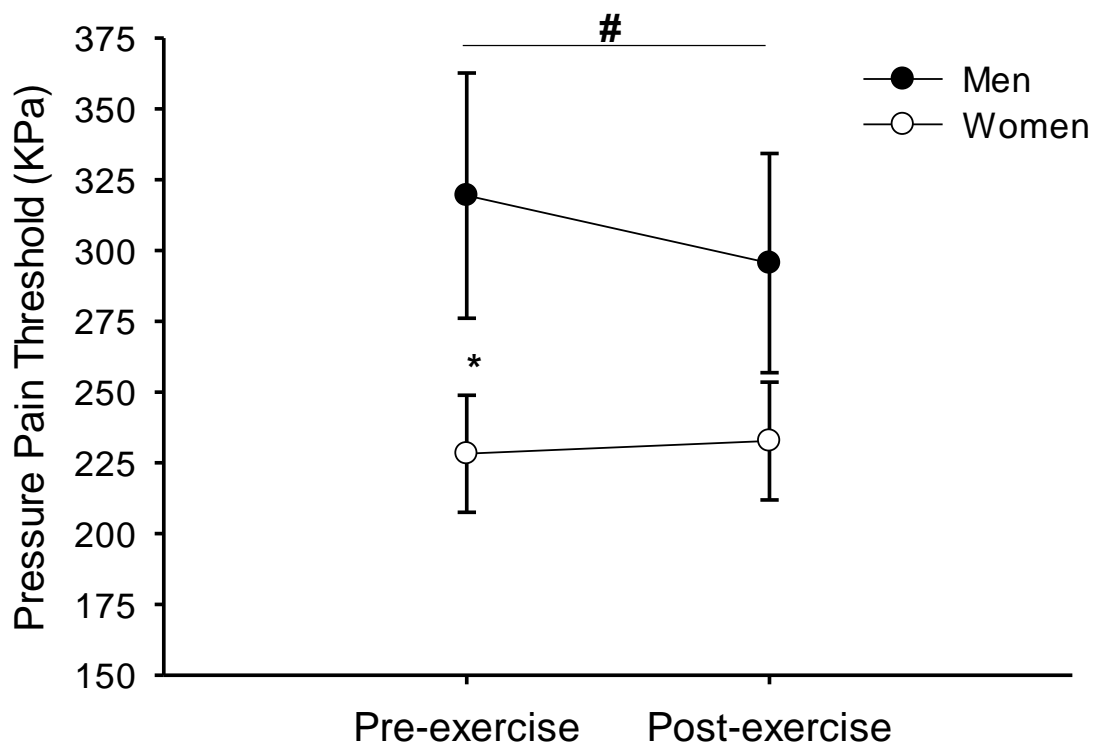
Figure 2.7. At baseline (pre-exercise), men demonstrate higher PPT at the nailbed (*). Following exercise, only men report a decrease in PPT (ie.. hyperalgesia; #).

Figure 2.8. Change in PPT at the Abdomen in Response to Trunk Flexion Exercise
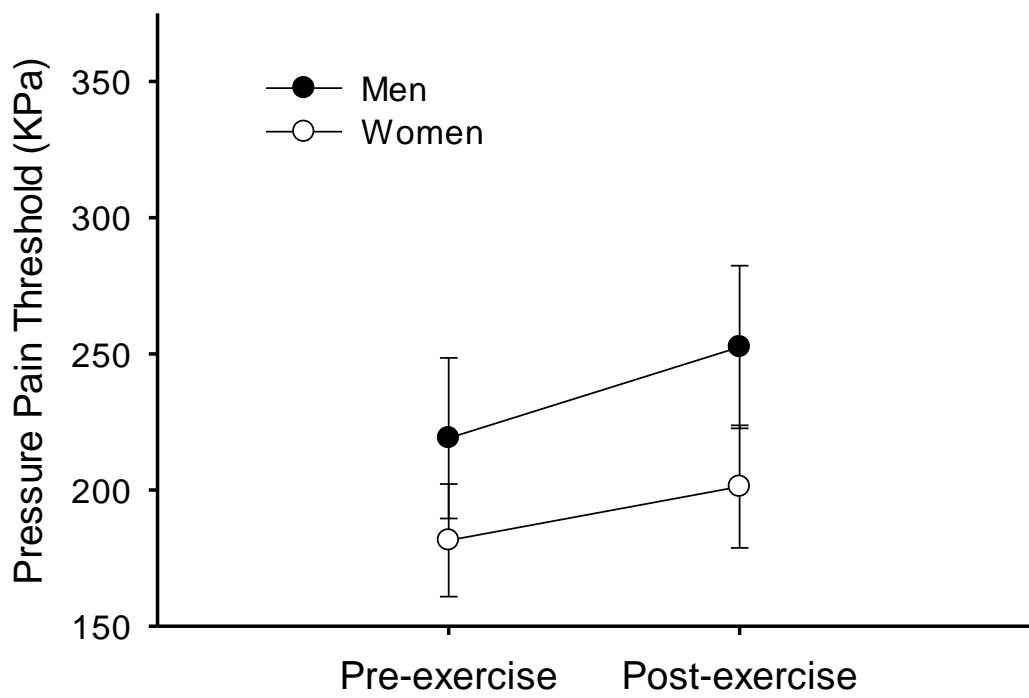
Figure 2.8. At baseline, men and women demonstrate similar PPTs before and after exercise. Following exercise, PPTs increased for both sexes (i.e hypoalgesia).

Figure 2.9. Association between EIH at the abdomen and Rectus Abdominis Muscle Thickness
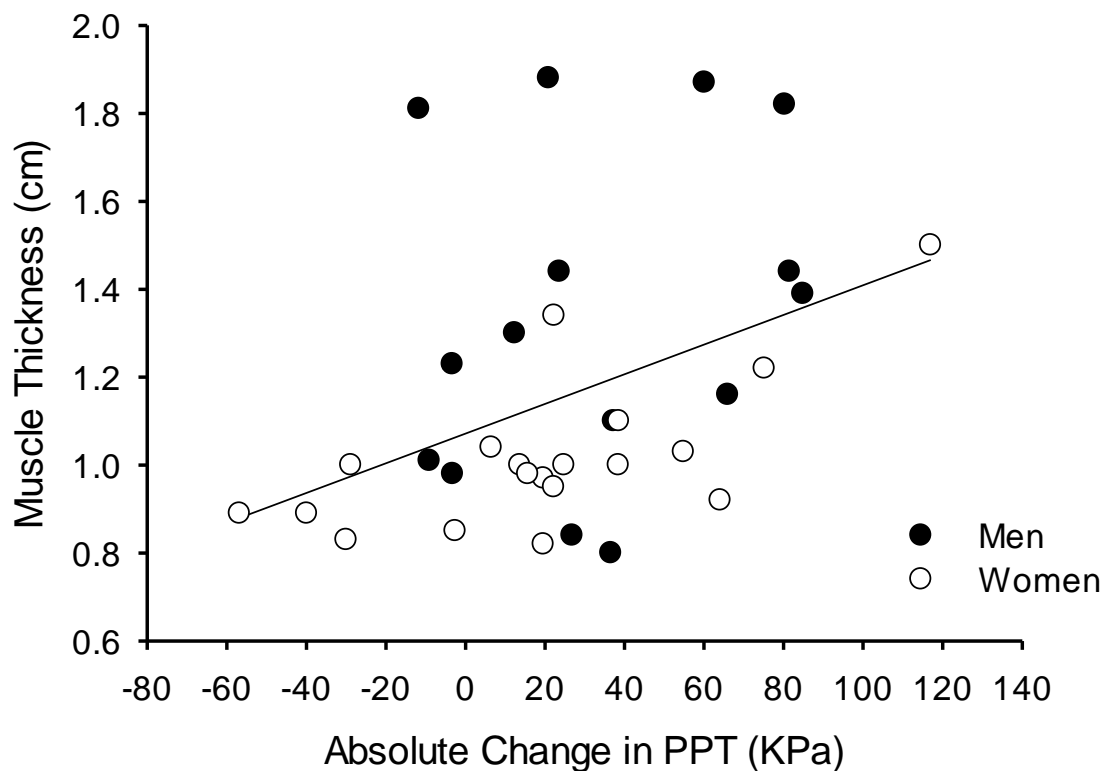
Figure 2.9. EIH was associated with muscle thickness of the left upper rectus abdominis. Individuals with thicker muscle demonstrated a greater increase in PPT following fatiguing exercise of the abdominal muscles.

DISCUSSION

The main findings of this study are: (1) EIH occurs locally (i.e., abdomen) following trunk flexor exercise in men and women; (2) men, but not women, report hyperalgesia at a site distal (i.e., nailbed) from the exercising muscles; and (3) EIH

measured at the abdominal muscle was associated with thickness of the rectus abdominis muscle.

To our knowledge, this is the first study to show EIH following fatiguing trunk flexor exercises. The hypoalgesia was localized to the exercising muscle, which is similar to others showing greater EIH at the exercising muscle compared with distal sites (Kosek and Lundberg 2003). Despite the local EIH effect that was similar between men and women, men reported hyperalgesia at the nailbed following the trunk flexor exercise while women reported no change in pain perception at the distal site. Interestingly, sex differences were also present in the baseline pain threshold at the nailbed with men reporting higher PPTs compared with women. Previously, we have shown associations between baseline pain and EIH (Hoeger Bement, Weyer et al. 2011, Lemley, Senefeld et al. 2016). In women with fibromyalgia, baseline pain sensitivity predicted reports of pain following exercise; those with lower pain sensitivity reported an increase in pain following exercise (Hoeger Bement, Weyer et al. 2011). Similarly, in this study, when men reported less baseline pain sensitivity compared with women they were more likely to report hyperalgesia following exercise.

Men typically demonstrate higher PPTs than women (Racine, Tousignant-Laflamme et al. 2012), which was shown at the nailbed site in this study, thus making the lack of a sex difference in pain threshold at the abdominal site in this study unique. The lack of a sex difference may be partially explained by the fact that women tend to have greater abdominal fat than men (Deering, Senefeld et al. 2017). Price and colleagues have shown higher pain thresholds in areas with excess subcutaneous fat (Price, Asenjo et al. 2013).

Individuals with thicker abdominal muscles demonstrated greater EIH. Previous work from our lab in a similar cohort demonstrated an association between lean muscle mass in the trunk and physical activity levels, with more active individuals having greater lean muscle (Deering, Senefeld et al. 2017). Physical activity has also been shown to be associated with endogenous pain inhibition (Lemley, Drewek et al. 2014). It is possible that individuals with greater muscle thickness were also more physically active, thus exhibited a greater increase in PPT in response to exercise.

Fatiguing exercise of the abdominal muscles, using an intermittent isometric protocol, successfully produced localized EIH in both men and women. Sex differences were present with men reporting less pain sensitivity at the nailbed, and following the trunk flexor exercise only men reported hyperalgesia at the nailbed (distal from the exercising muscle). Thus, baseline pain perception may be an important factor in the potential for EIH sex differences.

III.   TRUNK FLEXOR STRENGTH & FATIGABILITY IN WOMEN 8 & 26

WEEKS POSTPARTUM

Introduction

Background/rationale. Several physiological processes occur during pregnancy that impact the mother's musculoskeletal system. The abdominal muscles experience substantial stretch and increased inter-recti distance (IRD) commonly occurs (Boissonnault and Blaschak 1988, Coldron, Stokes et al. 2008). Hormones act on connective tissues throughout the mother's body, resulting in joint laxity, particularly in the pelvis (Kristiansson, Svardsudd et al. 1999, Negishi, Li et al. 2005, Chearskul 2006). The loss of passive lumbopelvic joint stabilization increases the importance and role of muscular stabilization, which is provided by the core muscles, including the abdominal muscles (Hodges, Kaigle Holm et al. 2003, Stokes, Gardner-Morse et al. 2011, Neumann 2016). Function of the abdominal muscles may also be compromised with pregnancy, although this is not well quantified.

Appropriate function of the abdominal muscles is critical for several life functions, including continence, breathing, and lumbopelvic stability (Hodges, Kaigle Holm et al. 2003, Lee, Lee et al. 2008). Postpartum women report impaired control of the abdominal muscles (Coldron, Stokes et al. 2008), and increased IRD in postpartum women is associated with abdominal and pelvic pain (Parker and Millar 2008). Dysfunction of the abdominal muscles is also associated with low back pain (Hodges and Richardson 1996, Hides, Boughen et al. 2010, Gildea, Hides et al. 2013). Up to 75% of pregnant women

experience low back pain or pelvic girdle pain during pregnancy (Albert, Godskesen et al. 2000, Wu, Meijer et al. 2004) and ~25% of these women continue to report pain after delivery (Ostgaard, Zetherström et al. 1994, Albert, Godskesen et al. 2000, Wu, Meijer et al. 2004). In addition, mode of delivery may impact recovery: Cesarean delivery involves profound disruption of the anterior abdominal wall (Corton, Leveno et al. 2009) and is associated with greater reports of postpartum pain and slower, more arduous recovery (Lobel and DeLuca 2007) than vaginal birth.

Given these reported changes in pain and recovery that suggest an impaired core musculoskeletal system in postpartum women, we investigated several aspects of muscle function including strength and fatigability of the abdominal muscles. Fatigability is an acute, activity-induced decline in the force or power of a muscle (Enoka and Duchateau 2008). This metric of muscle function plays an important role in motor performance, injury prevention, and rehabilitation (Enoka and Duchateau 2008). However, fatigability of the abdominal muscles is rarely assessed clinically. Additionally, the musculoskeletal system is not assessed as part of standard care in pregnant or postpartum women (Borders 2006, Cheng, Fowles et al. 2006, Liddle and Pennick 2015), and musculoskeletal impairments are often dismissed as 'normal'. Paid maternity leave in the United States, when available, is typically 6-8 weeks in duration (Vahratian and Johnson 2009) and often dictated by recovery of the smooth muscle of the uterus and perineal or surgical incision healing (Borders 2006, Archuleta 2015). Thus, we assessed abdominal function when women are typically returned to work (~8 weeks postpartum), as well as at 26 weeks postpartum, to determine recovery of the abdominal muscles.

Objectives. This study examined recovery of the maternal musculoskeletal system after vaginal and Cesarean delivery. Maximal strength and fatigability of the trunk flexor muscles in women 8-10 weeks and 24-26 weeks postpartum were compared with nulligravid controls. We focused on the abdominal muscles, which are the primary movers during trunk flexion. We *hypothesized* that (1) postpartum women would demonstrate significant deficits in maximal strength and fatigability of the trunk flexor muscles up to 26 weeks after delivery, and (2) women who underwent Cesarean delivery would have greater deficits in strength and fatigability than those who delivered vaginally.

Methods

Study design. Both a longitudinal and cross-sectional design were used to preserve subject numbers.

Setting. Data was collected from 2014-2016 in a University research laboratory. Recruitment was conducted from the University, physician referral from a local medical center, and the surrounding communities via print, internet and radio advertisements.

Participants. All participants were females between 18 and 45 years old, not pregnant at the time of testing, free of chronic health conditions, did not smoke or use smokeless tobacco, had no known neurological impairment, did not take medications that impact neuromuscular excitability (including anti-depressants), and had no medical or orthopedic contraindications to exercise. Control women had never been pregnant.

Thirty-two postpartum women (vaginal delivery n=19, Cesarean delivery n=13) and 22 control women participated in the study. Control women were also tested at two time points, separated by 16 weeks, to control for the effects of time and learning.

Variables and data sources/measurement.

Trunk flexion torque. Maximal and submaximal trunk flexion torques were measured with a Biodex System 4 dynamometer (Biodex, Shirley, New York) using a Back Flexion-Extension attachment. Maximal torque was assessed in six positions (upright sitting [0°]; 10°, 20°, 30°, and 40° of extension; 20°of flexion) to determine the strength of the trunk flexor muscles at different muscle lengths. Details of device set up and subject positioning are described elsewhere (Deering, Senefeld et al. 2017). In brief, subjects performed trunk flexion, as if curling the shoulders toward the hips, without engaging the lower extremities. A study investigator (physical therapist) visually inspected all trunk flexion trials, and any trials with lower extremity involvement were excluded.

A minimum of three trials of maximal voluntary contractions (MVC) were performed at each position, with 1 minute of rest between trials, until two trials were within 5% of each other. The maximum value was considered the MVC. Torque was recorded online using a Power 1401 A-D converter and Spike2 software [Cambridge Electronics Design (CED), Cambridge, UK]. Torque signals were digitized at 500 Hz and displayed on a monitor in front of the participant.

Hand Grip Strength. Bilateral handgrip strength was assessed with a JAMAR handgrip dynamometer (Patterson Medical, Warrenville, IL), with the arm positioned

fully extended at the side, as a control muscle group. Three trials were performed bilaterally, and the highest value for each hand was used.

Fatigability. Fatigability of the trunk flexor muscles was assessed with an intermittent, isometric submaximal fatiguing protocol. Subjects performed trunk flexion contractions in upright sitting ($0°$) in the Biodex attachment at 50% MVC (target line displayed on a monitor) for 6 seconds, followed by 4 seconds of rest. A 6-second MVC was performed every minute (in lieu of 50% MVC), followed by 4 seconds of rest. Strong verbal encouragement was provided to continue until failure. Task failure was identified as torque <50% MVC for $\geq$ 3 seconds of the 6-second contraction or an MVC of <50% of baseline MVC. The fatiguing protocol always ended with an MVC. Recovery of maximal strength was assessed with an MVC at 10 minutes and 20 minutes after task failure.

Inter-recti distance and rectus abdominis muscle thickness. Real-time ultrasound (GE Vivide; 8 LRS linear probe) was used to assess IRD and thickness of the rectus abdominis muscles in supine. Measurement of IRD was made 4 cm below the umbilicus, because increased IRD below the umbilicus is usually more severe.(Boissonnault and Blaschak 1988) Muscle thickness measurements of the right rectus abdominis were taken 2.5 cm above and below the umbilicus.

Physical activity. Self-reported physical activity was estimated with a questionnaire, which estimated the metabolic cost (METs) and the weekly metabolic equivalents (MET·hour·week^{-1}) of activities performed over the previous year (Kriska, Knowler et al. 1990). Physical activity around the time of experimental testing was quantified with ActiGraph accelerometers (ActiGraph Corp, Pensacola, Florida) worn around the waist

for 2 week days and 2 weekend days. Average minutes/day of moderate intensity exercise was quantified using ActiLife analysis software (ActiGraph).

Body composition. Dual x-ray absorptiometry (DXA) was used to estimate fat mass with a GE Lunar iDXA (GE Healthcare, Little Chalfont, United Kingdom).

Functional mobility. The six minute walk test (Ross, Murthy et al. 2010) was performed on an indoor course to quantify the maximal walk distance in six minutes.

Reported pain and low back pain related disability. The McGill Pain Questionnaire-short form (Melzack 1987) was used to quantify pain. The Oswestry Disability Index (Fairbank, Couper et al. 1980, Fairbank and Pynsent 2000, Fairbank 2014) was used to determine the impact of low back pain on performance of activities of daily living.

Bias. Postpartum women in this study reported minimal pain/disability.

Study size. Sample size was determined from a priori power analysis using G-Power (Heinrich-Heine-Universitat Dusseldorf, Dusseldorf, Germany) and the main variables of strength and fatigability.

Statistical methods. Differences between groups (postpartum and control) were determined for subject characteristics, pre-exercise MVC torque, IRD, and time-to-task failure (fatigability) using independent samples t-tests. Differences between groups for torque-angle curve and recovery of MVC torque following fatiguing exercise were assessed using repeated measures analysis of variance (ANOVA) with group as a between-subjects factor. Impact of method of delivery (Cesarean vs vaginal) was assessed with independent samples t-tests for subject characteristics, MVC torque and fatigability. Pearson correlation was used to examine relationships between scale level variables that demonstrated a linear relationship. Spearman correlation was used to

examine relationships between variables that had a curvilinear relationship and/or were ordinal level data. Significance was set as $p<0.05$. Missing data was excluded analysis by analysis. Statistical analyses were performed with SPSS version 24 software (IBM, Armonk, NY, USA).

Results

Participants. Twenty-nine postpartum women (Vaginal delivery n=18, Cesarean delivery n=11) and 15 control women completed initial (8-10 weeks postpartum) testing. Twenty-eight postpartum women (Vaginal delivery n=17, Cesarean delivery n=11) and 14 control women completed testing at follow up (24-26 weeks postpartum). For paired samples testing, eight control women and 26 postpartum women (Vaginal delivery n=17, Cesarean delivery n=9) had complete data sets at both time points. Loss of follow up for seven control women and two women from the Cesarean group was due to schedule conflicts. One woman from the vaginal group did not complete follow up testing due to pregnancy. Two women from the Cesarean group completed testing only at 24-26 weeks postpartum.

Descriptive data. Group characteristics, including body composition, handgrip strength, muscle thickness, and physical activity, are presented for controls vs postpartum women in Table 3.1 and vaginal delivery vs Cesarean delivery in Table 3.2.

Table 3.1. Subject characteristics: Control vs Postpartum

Variable	INITIAL (8wks Postpartum)		FOLLOW UP (26 wks Postpartum)	
	Control (n=15)	Postpartum (n=29)	Control (n=14)	Postpartum (n=28)
Age (yrs)	25.5 ± 5.3	31.4 ± 5.2*	25.8 ± 6.1	32.0 ± 5.1*
Weight (kg)	63.6 ± 12.7	74.4 ± 13.4*	62.7 ± 7.8	71.4 ± 14.0*
Height (cm)	166.6 ± 7.1	164.1 ± 4.6	166.9 ± 8.4	164.1 ± 4.8
BMI (kg/m^2)	22.7 ± 3.8	27.6 ± 5.0*	22.4 ± 1.8	26.9 ± 5.1*
Body Fat (%)	31.0 ± 5.4	38.5 ± 6.9*	31.8 ± 4.6	36.7 ± 8.4*
McGill Pain Questionnaire-short form	0.4 ± 1.0	0.3 ± 0.7	0.3 ± 0.7	0.9 ± 2.0
Oswestry Disability Index	1.1 ± 2.5	4.6 ± 5.4*	0.9 ± 1.9	4.7 ± 7.1
Thickness of right rectus abdominis muscle belly (2.5 cm above umbilicus) (cm)	1.0 ± 0.2	0.8 ± 0.2*	1.0 ± 0.1 (n=13)	0.8 ± 0.2*
Thickness of right rectus abdominis muscle belly (2.5 cm below umbilicus) (cm)	1.0 ± 0.2	0.8 ± 0.2*	0.9 ± 0.1 (n=13)	0.8 ± 0.2
Average minutes/day of moderate intensity physical activity	47.8 ± 23.4 (n=9)	18.8 ± 18.8* (n=20)	31.2 ± 14.0 (n=7)	16.7 ± 10.5* (n=13)
Self-reported physical activity over the previous 12 months (MET·hours·week^{-1})	43.0 ± 28.3 (n=14)	22.2 ± 19.2* (n=27)	34.0 ± 25.1	14.9 ± 17.3* (n=25)
Distance walked in 6 minutes (m)	686.2 ± 58.7	640.0 ± 64.8	693.3 ± 58.2	652.7 ± 65.1
Hand grip maximal strength, right hand (kg)	33.4 ± 6.7	33.1 ± 5.9	34.2 ± 5.3	34.1 ± 6.5 (n=27)
Hand grip maximal strength, left hand (kg)	31.4 ± 5.9	31.1 ± 4.9	30.8 ± 4.5	32.3 ± 5.6 (n=27)
Change in MVC torque at end of fatiguing exercise protocol (% MVC)	-26.2 ± 15.9	-14.6 ± 32.4	-30.0 ± 13.4	-24.0 ± 18.8

* Indicates $p<0.05$

Table 3.2. Subject Characteristics: Vaginal vs Cesarean Delivery

Variable	8 weeks Postpartum		26 weeks postpartum	
	Vaginal (n=18)	Cesarean (n=11)	Vaginal (n=17)	Cesarean (n=11)
Age (yrs)	30.6 ± 6.0	32.8 ± 3.5	31.4 ± 5.8	33.0 ± 4.0
Weeks postpartum	9.4 ± 1.1	9.3 ± 0.5	26.1 ± 1.6	26.2 ± 0.6
Total Number of Pregnancies	2.1 ± 1.2 (n=17)	3.0 ± 1.9 (n=10)	2.1 ± 1.1 (n=15)	3.0 ± 2.1 (n=9)
Duration of Most Recent Pregnancy (weeks)	39.3 ± 1.0 (n=14)	38.1 ± 1.2* (n=10)	39.3 ± 1.0 (n=12)	38.3 ± 1.4 (n=9)
Weight (kg)	74.3 ± 14.4	74.2 ± 12.2	70.9 ± 15.3	72.4 ± 12.4
Height (cm)	164.6 ± 4.3	163.1 ± 5.3	165.1 ± 4.8	162.6 ± 4.8
BMI (kg/m^2)	27.5 ± 5.4	27.8 ± 4.3	26.4 ± 5.6	27.5 ± 4.3
Body Fat %	39.0 ± 7.0	37.7 ± 7.0	36.1 ± 8.8	37.7 ± 8.2
McGill Pain Questionnaire-short form	0.4 ± 0.8	0.2 ± 0.5	1.2 ± 2.4	0.3 ± 0.7
Oswestry Disability Index	6.4 ± 6.0	1.6 ± 2.5*	5.4 ± 7.9	3.6 ± 5.9
Thickness of right rectus abdominis muscle belly (2.5 cm above umbilicus) (cm)	0.8 ± 0.2	0.8 ± 0.1	0.8 ± 0.2	0.8 ± 0.1
Thickness of right rectus abdominis muscle belly (2.5 cm below umbilicus) (cm)	0.8 ± 0.2	0.8 ± 0.2	0.8 ± 0.3	0.8 ± 0.2
Average minutes/day of moderate intensity physical activity	17.1 ± 19.1 (n=10)	20.4 ± 19.4 (n=10)	16.8 ± 11.2 (n=10)	13.1 ± 4.9 (n=3)
Self-reported physical activity over the previous 12 months (MET·hours·week$^{-1)}$)	22.0 ± 16.3 (n=17)	22.6 ± 24.3 (n=10)	15.4 ± 20.8 (n=15)	14.3 ± 11.3 (n=10)
Distance walked in 6 minutes (m)	645.0 ± 62.0	631.8 ± 71.3	663.4 ± 60.8	636.1 ± 70.9
Hand grip maximal strength, right hand (kg)	33.4 ± 5.9	32.5 ± 6.1	34.9 ± 6.5	32.7 ± 6.6 (n=10)
Hand grip maximal strength, left hand (kg)	31.7 ± 5.2	30.2 ± 4.6	33.2 ± 5.9	30.7 ± 4.9 (n=10)

Change in MVC torque at end of fatiguing exercise protocol (% MVC)	-12.0 ± 27.4 (n=16)	-18.4 ± 39.7	-22.9 ± 21.0	-25.8 ± 15.4

* Indicates *p*<0.05

Outcome Data & Main Results.

Maximal Torque Across Different Positions (Torque-Angle Curve). Postpartum women were weaker than controls across all positions at 8 weeks (39.6 ± 22.6 Nm vs 65.8 ± 29.2 Nm, respectively, *p*<0.001; Figure 3.1A) and 26 weeks (36.5 ± 19.8 Nm vs 54.3 ± 24.2 Nm, *p*=0.001; Figure 3.1B) postpartum. The shape of the torque-angle curve was similar between groups at both time points (initial: position × group, *p*=0.927; follow up: position × group, *p*=0.766), with both control and postpartum women generating greatest trunk flexion MVC torque at 40 degrees of extension (effect of position, *p*<0.001 at both time points).

Mode of Delivery: There was no difference in the torque-angle curve between delivery types at 8 weeks (position: *p*<0.001; position × delivery type: *p*=0.169; delivery type: *p*=0.058; Figure 3.1C) or 26 weeks (position: *p*<0.001, position × delivery type: *p*=0.964, delivery type: *p*=0.485; Figure 3.1D).

Figure 3.1. Torque-Angle Curve
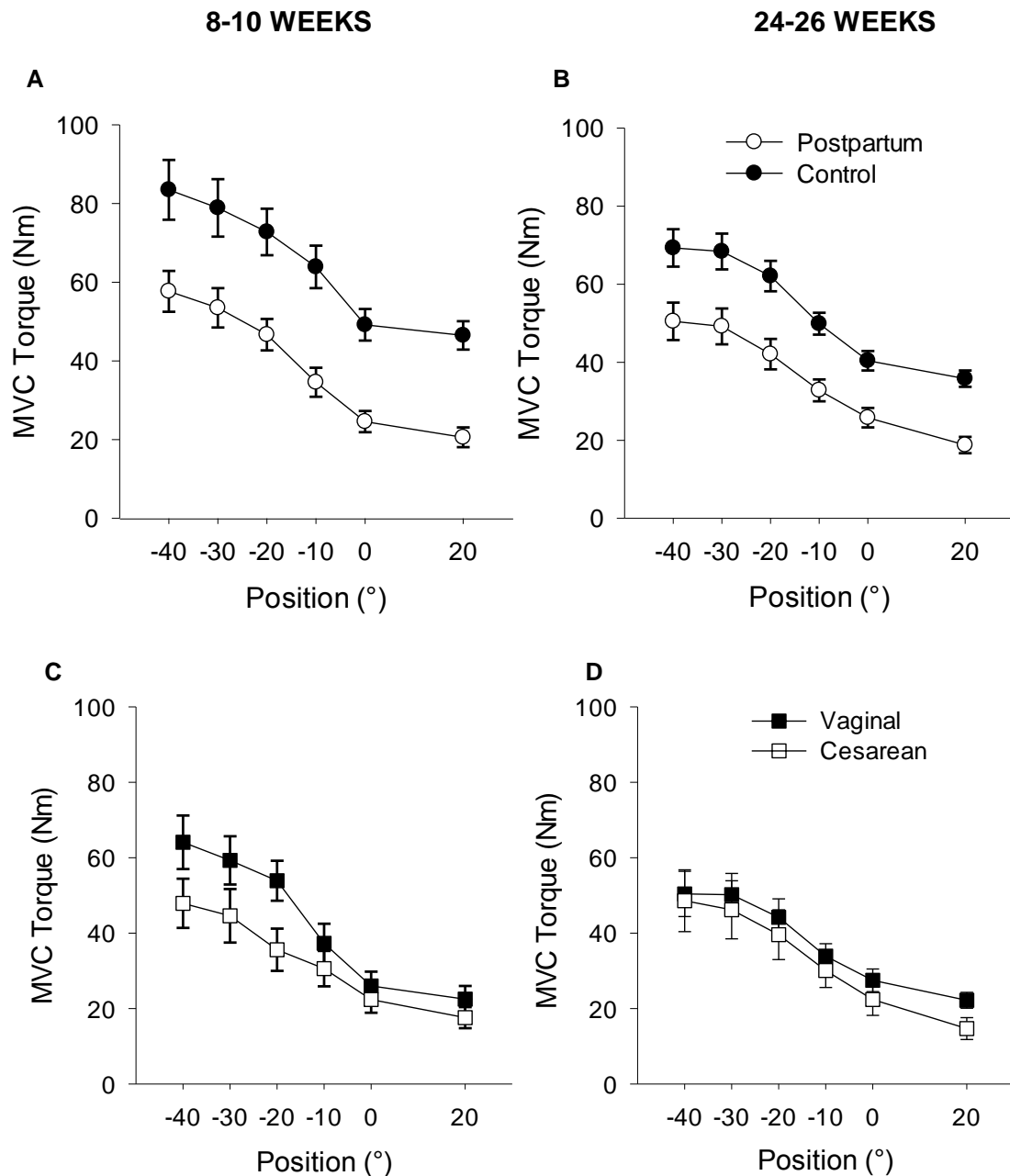
Figure 3.1. Torque-angle curve for the trunk flexor muscles at the initial and follow up time points for postpartum vs control [A & B] and vaginal vs Cesarean delivery [C & D]. Negative numbers indicate positions of trunk extension, upright sitting is 0°, and positive numbers indicate positions of trunk flexion. Postpartum women had lower maximal trunk flexion torque across all positions at both time points compared to control. However, the torque-angle curve shape was similar for all groups. There were no differences between delivery types (vaginal vs Cesarean).

Fatigability. Postpartum women had a shorter time to task failure (i.e. greater fatigability) than control women at 8 weeks postpartum (189 ± 156 s vs 644 ± 327 s, respectively; $p<0.001$; Figure 3.2A). By 26 weeks, postpartum women demonstrated longer time-to-task failure (i.e. improved fatigability) ($p=0.015$), but were more fatigable than control women (288 ± 167 s vs 605 ± 396 s; $p=0.011$; Figure 3.2A).

Mode of Delivery: At 8 weeks postpartum, the Cesarean delivery group demonstrated a shorter time-to-task failure (greater fatigability) than the vaginal delivery group (99 ± 58 s vs 244 ± 173 s; $p=0.004$; Figure 3.2B). By 26 weeks postpartum, there was no difference in time-to-task failure between delivery groups (262 ± 168 s vs 304 ± 169 s; $p=0.523$; Figure 3.2B). The vaginal delivery group showed no change in time-to-task failure from 8 to 26 weeks ($p=0.306$), but the Cesarean delivery group demonstrated improvement in time-to-task failure ($p=0.005$).

Figure 3.2. Fatigability of the Trunk Flexor Muscles
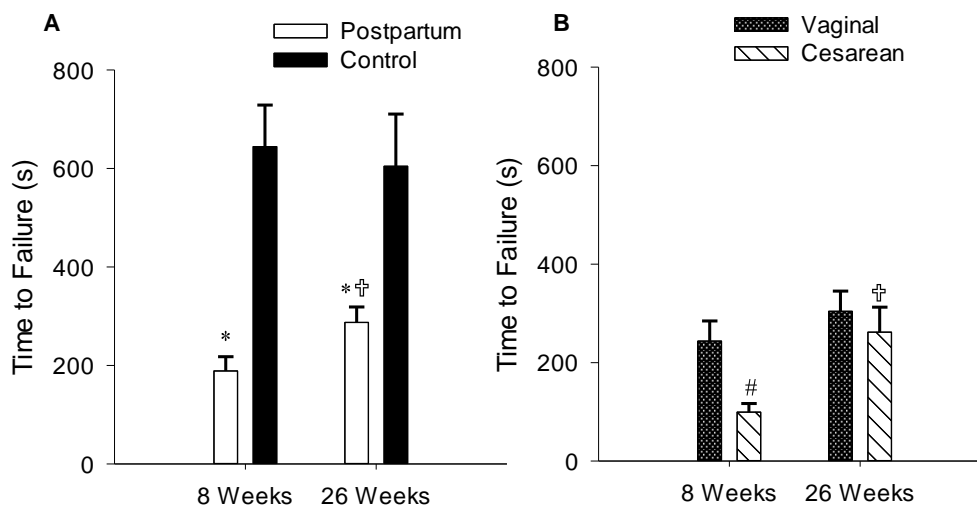
Figure 3.2. Time-to-task failure for the intermittent isometric submaximal trunk flexion fatiguing exercise at time points for postpartum vs control [A] and vaginal vs Cesarean

delivery [B]. *=group difference at the time point (postpartum vs control); ☩=improvement compared to initial timepoint; #=delivery group difference at the time point (vaginal vs Cesarean).

__Pre-Exercise Maximal Trunk Flexion Torque__: Trunk flexion MVC torque was less for the postpartum women than control women at both 8 weeks (28.6 ± 12 Nm vs 46.5 ± 26.1 Nm; $p=0.022$; Figure 3.3A) and 26 weeks postpartum (24.6 ± 10.1 Nm vs 44.1 ± 16.6 Nm; $p=0.001$; Figure 3.3B).

At task failure, the postpartum and control women had a similar reduction in MVC torque, at both the 8 week and 26 week time points (Table 3.1). At 8 weeks, the MVC torque of postpartum women was lower 20 minutes following fatiguing exercise, while the MVC torque of control women had recovered by 10 minutes post-exercise (Time, $p<0.001$; Time $\times$ group, $p<0.001$; Group, $p=0.001$; Figure 3.3A). At 26 weeks, postpartum women demonstrated a recovery (increase) of MVC torque post-exercise that was similar to control women, though postpartum women demonstrated lower MVC torque than control women at all time points after exercise (Time, $p<0.001$; Time $\times$ Group, $p=0.463$; Group, $p<0.001$; Figure 3.3B).

Mode of Delivery: There were no differences between vaginal and Cesarean delivery for pre-exercise MVC strength at 8 weeks (31.4 ± 13.0 Nm vs 24.0 ± 8.8 Nm, respectively, $p=0.106$, Figure 3.3C) nor at 26 weeks (24.9 ± 11.4 Nm vs 24.3 ± 8.1 Nm, respectively, $p=0.886$, Figure 3.3D). There was also no difference in MVC torque recovery following fatiguing exercise at 8 weeks (time, $p=0.775$; time $\times$ delivery type, $p=0.592$; delivery type, $p=0.829$) and 26 weeks (time, $p=0.006$; time $\times$ delivery type, $p=0.163$; delivery type, $p=0.386$).

Figure 3.3. Trunk Flexor Strength Before and After Fatiguing Exercise
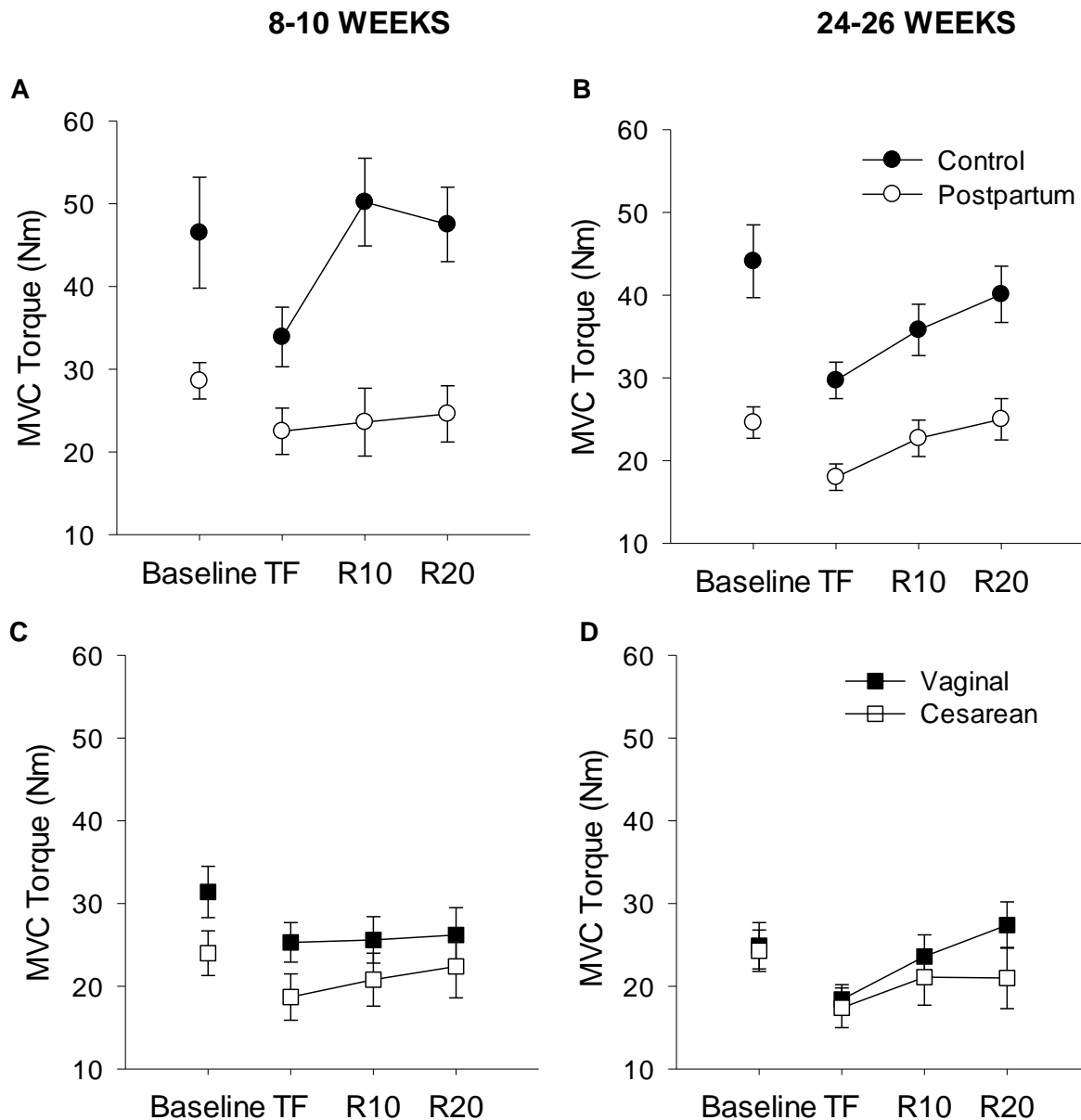
Figure 3.3. Trunk flexion MVC strength before fatiguing exercise (baseline), immediately following fatiguing exercise (task failure, TF), and 10 minutes (R10) and 20 minutes (R20) after fatiguing exercise at the initial time point and follow up time point for control vs postpartum [A & B] and vaginal vs Cesarean [C & D] groups. Postpartum women generate lower maximal torque than control women at all time points. Postpartum women demonstrate impaired recovery of MVC strength up to 10 weeks postpartum [A], but show a similar recovery pattern to control women at 26 weeks postpartum [B]. No statistical difference is present between modes of delivery at either time point [C & D]. Postpartum women demonstrate a decline in baseline MVC strength from 8-26 weeks, driven by a loss of strength for women in the vaginal delivery group.

Inter-recti distance. Postpartum women demonstrated greater IRD than controls at 8 weeks (1.4 ± 1.1 cm vs 0.4 ± 0.2 cm, $p<0.001$) and 26 weeks (1.3 ± 1.1 cm vs 0.3 ± 0.2 cm, $p<0.001$).

Mode of delivery. There was no difference in IRD between vaginal and Cesarean delivery types at 8 weeks (1.2 ± 1.1 cm vs 1.8 ± 1.2 cm, respectively, $p=0.271$) or 26 weeks (1.2 ± 1.0 cm vs 1.5 ± 1.3 cm, respectively, $p=0.431$).

Associations (postpartum and control).

Trunk flexor MVC torque was associated with fatigability (8 weeks: r=0.602, $p<0.001$ & 26 weeks: r=0.415, $p=0.006$), thickness of the rectus abdominis (8 weeks: r=0.311, $p=0.040$ & 26 weeks: r=0.388, $p=0.012$), self-reported physical activity (8 weeks: r=0.430, $p=0.005$) and the six-minute walk (8 weeks: r=0.306, $p=0.044$ and 26 weeks: r=0.449, $p=0.003$). Stronger women had a longer time-to-task failure, greater rectus abdominis thickness, were more active, and walked further in six minutes.

Fatigability was associated with body fat (8 weeks: r=-0.342, $p=0.023$ & 26 weeks: r=-0.402, $p=0.008$) and IRD (8 weeks: r_s=-0.548, $p<0.001$ & 26 weeks: r_s=-0.484, $p=0.002$), such that women with greater total body fat and a greater IRD were more fatigable.

Discussion

The novel findings are that the trunk flexor muscles of postpartum women were weaker and more fatigable than nulligravid women, and these impairments in trunk

strength and fatigability persisted at 26 weeks postpartum. The strength deficits were specific to the trunk flexor muscles, as there was no difference in hand grip strength between groups. Furthermore, mode of delivery impacted muscle endurance: women who had a Cesarean delivery demonstrated greater trunk flexor fatigability at 8 weeks postpartum than women who delivered vaginally. A larger IRD was associated with greater fatigability at both time points. Furthermore, greater trunk flexor strength was associated with lower fatigability and greater functional mobility.

This is the first study to establish that postpartum women demonstrate deficits in strength and increased fatigability of core muscles, which are important to many daily activities. At 8 weeks, the deficits, relative to controls, were 38% in strength and 71% in fatigability, and 44% and 52%, respectively, at 26 weeks; long past when women have returned to work (~8 weeks postpartum). Strength deficits in postpartum women were localized to the trunk flexor muscles, which highlights the need for specific postpartum assessment and rehabilitation of the trunk flexors, including the abdominal muscles.

At 8 weeks after delivery, postpartum women also demonstrated impaired *recovery* of maximal strength after fatiguing exercise, as evidenced by reduced MVC strength 20 minutes after exercise. In contrast, control women had returned to baseline strength 10 minutes after exercise. This prolonged reduction in maximal strength may increase risk of injury when performing repetitive tasks, such as lifting and carrying. Furthermore, postpartum women in this study had only sub-clinical levels of pain and low back pain-related disability, but they still demonstrated severe deficits in strength and fatigability. Further research is needed to determine if postpartum women with clinically significant pain and disability experience even greater deficits in core strength and fatigability.

Method of delivery was a contributing factor to the increased fatigability of postpartum women at 8 weeks after delivery, with Cesarean delivery being associated with greater fatigability. Women who had a Cesarean delivery often have greater pain reports in the immediate postpartum period and report a more difficult postpartum recovery than women who delivered vaginally.(Lobel and DeLuca 2007) However, no differences exist in the length of paid maternity leave based on delivery method.(Archuleta 2015) This research suggests that women who undergo Cesarean delivery require a longer period of time to recover from the musculoskeletal deficits experienced from pregnancy and childbirth than women who experience a vaginal delivery. Given the severe deficits in abdominal function of postpartum women, it appears all women would benefit from rehabilitative interventions; however, this rehabilitation is even more crucial for women who deliver by Cesarean section.

Trunk flexor strength appears to be a critical factor in musculoskeletal recovery after pregnancy and childbirth. Stronger women were less fatigable and demonstrated better functional mobility. The association between strength and fatigability has also been observed in healthy young men and women,(Deering, Senefeld et al. 2017) supporting the importance of core strength. Strength was also associated with thickness of the rectus abdominis muscle and with self-reported physical activity over the previous year. Thus, our results suggest that lack of physical activity in postpartum women may have contributed to lower trunk flexor strength. Physical activity levels of postpartum women were significantly lower than those of control women, and declined even further between 8 and 26 weeks postpartum. Further, postpartum women did not meet the recommended average of 30 minutes per day of moderate intensity physical activity (Leavitt 2008).

These results provide a rationale for prescription of individualized exercise for postpartum women to offset the strength decrements, and thus the impairments in fatigability and functional mobility, seen in this study.

The astounding deficits in trunk flexor strength and fatigability in postpartum women in this study support the need for skilled assessment of the musculoskeletal system by health care providers who have expertise in the examination, diagnosis, and treatment of musculoskeletal disorders. Incorporating physiatrists and physical therapists in the standard care of pregnant and postpartum women may offset some of the neuromuscular impairments seen in this study, and may improve the incidence and severity of other pregnancy-related musculoskeletal disorders, such as low back pain and pelvic girdle pain. Further research is needed to determine the impact of rehabilitation on the musculoskeletal health of pregnant and postpartum women.

IV.   FATIGABILITY OF THE LUMBOPELVIC STABILIZING MUSCLES &

EXPERIMENTAL PAIN PERCEPTION IN WOMEN 8 & 26 WEEKS

POSTPARTUM

Introduction

Pregnancy and child birth have a significant impact on the musculoskeletal

system of the mother. Hormonal changes during pregnancy facilitate the softening of

connective tissue, which leads to joint laxity, particularly in the pelvic joints (Chearskul

2006). Vaginal birth can further disrupt the pelvic joints and/or cause injury to the pelvic

floor muscles, especially when intervention is needed in the form of instrumentation,

such as forceps or vacuum (Ashton-Miller and Delancey 2009). Cesarean delivery also

causes further trauma to the fascia of the anterior abdominal wall and the abdominal

musculature (Gilstrap III, Cunningham et al. 2002). Additionally, the combination of

hormonal changes and the progressive and prolonged stretch on the anterior abdominal

wall contributes to an increase in inter-recti distance (IRD), or an increased separation of

the rectus abdominis muscles (Boissonnault and Blaschak 1988, Gilleard and Brown

1996, Coldron, Stokes et al. 2008). Pregnancy and child birth have been associated with

a number of physical impairments which are commonly treated by physical therapists,

such as low back pain, pelvic girdle pain and incontinence (MacLennan, Taylor et al.

2000, Gutke, Ostgaard et al. 2008, Parker and Millar 2008, Sjodahl, Gutke et al. 2013).

The abdominal muscles and pelvic floor muscles have been shown to play a role in stability of the spine and pelvis (Hodges, Kaigle Holm et al. 2003, Pool-Goudzwaard, van Dijke et al. 2004), and dysfunction of these muscle groups has been linked with pain syndromes (Hodges and Richardson 1996, Hodges and Moseley 2003, Hungerford, Gilleard et al. 2003, Pool-Goudzwaard, Slieker ten Hove et al. 2005, Gildea, Hides et al. 2013). The fascial integrity of the abdominal wall has been shown to be critical to the transfer of force generated by the abdominal muscles to the skeletal system (Brown and McGill 2009), and this integrity can be assessed with ultrasound by measuring inter-recti distance. Currently, the Active Straight Leg Raise (ASLR) test is used as a clinical measure of stability of the lumbar spine and pelvis, ability to perform an abdominal bracing maneuver, and measure of posterior pelvic pain severity, and has been validated in both pregnant and postpartum populations (Mens, Vleeming et al. 1999, Mens, Vleeming et al. 2002, Liebenson, Karpowics et al. 2009, Mens, in 't Veld et al. 2012).

Assessment of the musculoskeletal system is not part of standard postpartum care at this time (Borders 2006). Furthermore, clinical measures of abdominal muscle function, such as manual muscle testing (MMT), are often subjective and insensitive, and frequently limited to assessing strength alone. Maintenance of sustained and intermittent abdominal muscle contractions, however, is relevant to daily functional tasks and is characterized as fatigability of the muscle group. Fatigability is defined as the reduction in maximal or required force or power of a muscle in response to activity (Enoka and Duchateau 2008), and it is an important metric of muscle function that is often overlooked in clinical assessment. Fatigability can also be quantified as a reduction in the maximal strength or power, or as the amount of time an individual is able to

successfully sustain a motor task, known as time-to-task failure. Chapter 3 of this dissertation reported that the trunk flexor muscles of postpartum women are significantly more fatigable at 26 weeks postpartum than controls. It is unknown if the lumbopelvic stabilizing muscles demonstrate similar deficits in fatigability after pregnancy.

In this study, the ASLR test was modified into a fatigue task to assess the fatigability of the lumbopelvic stabilizing muscles in nulligravid women and women who were up to 26 weeks postpartum, and to determine feasibility of this test for clinical use. Participants also performed the six-minute walk test and a number of questionnaires. We hypothesized that postpartum women would be more fatigable (have a shorter time-to-task failure) than control women during the newly developed ASLR fatigue task, and that time-to-task failure would be associated with performance on the six-minute walk test and questionnaires. We also hypothesized that the time to task failure of the ASLR fatigue test would be associated with the time to task failure of the trunk flexor muscles measured in the Biodex dynamometer that was reported in chapter 3.

Methods

Subjects. Twenty-three control women (26.7 ± 9.9 years) and 31 postpartum women (31.4 ± 5.2 years; vaginal delivery n=18, Cesarean delivery n=13) participated in the study. All participants were from the original study described in Chapter 3, and met the same inclusion and exclusion criteria, and provided written informed consent. Participants completed two experimental sessions, separated by one to seven days, at two time points. Postpartum women completed testing between 8-10 weeks after delivery and returned to the laboratory between 24-26 weeks postpartum. Control women

completed their initial testing sessions and returned 16-18 weeks later to repeat the testing sessions. Study approval was obtained by the Institutional Review Boards at Marquette University and the Medical College of Wisconsin, and the Office of Clinical Research and Innovative Care Compliance at Froedtert Hospital.

Session one consisted of measurement of height and weight, a dual x-ray absorptiometry (DXA) scan to estimate body composition, manual muscle testing, experimental pain testing, the active straight leg raise test, and the active straight leg raise fatigue task. Session two involved performance of the six-minute walk test and completion of multiple questionnaires regarding pain, sleep quality, physical activity, pelvic floor dysfunction, disability, and postpartum depression. Participants also wore a triaxial accelerometer for four days outside of the laboratory to quantify physical activity levels.

Standard Clinical Measurements of Abdominal Muscle Function

Manual Muscle Testing. Participants were positioned on a plinth in supine with legs extended, without a pillow behind their head. Participants were instructed to lift their head and shoulders up off the table as far as possible without moving their legs. Strength was graded on a 1-5 scale, based on the position of the participants' upper extremities when they were able to perform trunk flexion to the point of clearing the inferior angle of the scapula from the plinth. A score of 5 was awarded if the participant could clear the inferior angle of the scapula with both hands behind their head. If this position was unsuccessful, the arms were then placed across the chest and trunk flexion was attempted again. If successful in this position, a grade of 4 was assigned. If

unsuccessful, the participant was then cued to reach toward their toes with both arms while performing trunk flexion, which was scored as a 3 if successful. A grade of 2 required the participant to assume a supine hook lying position, with both knees bent and feet flat on the plinth. If the participant was unable to clear the inferior angle of the scapula in any of these positions, a grade of 1 would be assigned if the participant could produce a forceful cough (Hislop and Montgomery 2002).

Active Straight Leg Raise Test. The ASLR test assesses load transfer between the lower extremity and the trunk, and stability of the lumbar spine and pelvis, and relies on appropriate activation and sufficient strength of the abdominal muscles, among other muscle groups, to maintain stability. While lying supine on a plinth, participants were asked to raise one leg 20 cm off the plinth, hold at 20 cm for 5 seconds, and slowly lower the leg back to the plinth. Stability of the spine and pelvis was assessed with an inflatable air bladder that was positioned under the participants' lumbopelvic region and inflated to 40 mm Hg. The change in cuff pressure was recorded for each leg. Participants were also asked to rate how difficult, on a scale of 0-5 (0=not difficult at all, 5=unable to lift leg), it was to raise their leg off of the plinth. For ratings above zero, the test was performed again, this time with the examiner providing manual compression to the pelvis. If the difficulty rating decreased with manual compression, the test was considered positive for instability of the pelvis (Mens, Vleeming et al. 2001, Mens, Vleeming et al. 2002, Vleeming, Albert et al. 2008, Liebenson, Karpowics et al. 2009, Mens, in 't Veld et al. 2012). Pain ratings were also given if the participant experienced any pain in the lumbar spine or pelvic areas while performing the task. Pain was rated on a 0-10 scale, with 0 being no pain and 10 being worst possible pain.

Novel Clinical Measurement of Fatigability of the Lumbopelvic Stabilizers

Active Straight Leg Raise Fatigue Task. The ASLR test was modified into a fatigue task as a test of fatigability of the muscles that stabilize the lumbopelvic region and that could be easily performed in clinical settings. Participants performed the ASLR test prior to performing the fatigue task. If the participant rated the difficulty of raising the leg the same on both sides, the dominant leg (self-reported) was used for the fatigue task. If the difficulty ratings were different between legs, or if the participant had a positive test and/or a painful side, the leg that was less difficult (or not painful) was used. Participants lifted the test leg to 20 cm and were instructed to hold their leg in that position for as long as possible. Participants were also asked to maintain the pressure in the cuff beneath their back as close to 40 mm Hg as possible. Visual feedback on cuff pressure was provided throughout the task, but no instruction was given on how to affect cuff pressure.

Participants provided Ratings of Perceived Exertion (RPE) and pain ratings on a 0-10 scale at random intervals (every 45-60 seconds) throughout the test and at task failure. Task failure was defined as an inability to maintain the heel of the test leg ≥10 cm off the plinth and/or a change in cuff pressure ≥20 mm Hg.

Functional Test: Six Minute Walk

In order to assess muscular and cardiovascular endurance during functional mobility, the six minute walk test was performed (Ross, Murthy et al. 2010). Participants were instructed to walk as quickly as possible, without running, for six minutes on an

indoor walking track. The distance walked was then measured. Standard instructions and encouragement were provided for each participant. Distance walked was also used to estimate peak oxygen uptake as a measure of cardiovascular fitness (Ross, Murthy et al. 2010).

Physical Activity

Self-reported Physical Activity. The Physical Activity Questionnaire (Kriska, Knowler et al. 1990) was used to allow participants to self-report physical activity over the previous year. In short, the questionnaire evaluates both recreational and occupational physical activity and quantifies it in metabolic equivalents per hour per week (MET·hour·week^{-1}).

Accelerometry. Physical Activity around the time of testing was quantified using triaxial accelerometers (Actigraph, Pensacola, FL) worn around the waist for four days, including two weekend days. Average minutes per day of moderate intensity exercise was determined (ActiLife software, Actigraph) in accordance with American College of Sports Medicine and the American Heart Association physical activity recommendation of 30 minutes of moderate intensity exercise five days per week (Haskell, Lee et al. 2007).

Questionnaires

Pain was assessed with the McGill Short Form Pain Questionnaire (Melzack 1987) prior to performance of the six-minute walk test. The impact of low back and pelvic girdle pain on daily function was assessed with the Oswestry Low Back Disability

Questionnaire (Fairbank, Couper et al. 1980, Fairbank and Pynsent 2000) and the Pelvic

Girdle Questionnaire (Stuge, Garratt et al. 2011). The Fear Avoidance Beliefs

Questionnaire (Waddell, Newton et al. 1993) and The Pain Catastrophizing Scale

(Sullivan, Bishop et al. 1995) were used to gauge participant's thoughts and feelings

regarding pain. Pelvic floor symptoms were assessed with the Pelvic Floor Distress

Inventory (Barber, Kuchibhatla et al. 2001) and the Pelvic Pain and Urgency/Frequency

Patient Symptom Scale (Parsons, Dell et al. 2002). Sleep disturbances were quantified

with the Pittsburgh Sleep Quality Index (Buysse, Reynolds et al. 1989). Postpartum

depression was assessed with the Edinburgh Postnatal Depression Scale (Cox, Holden et

al. 1987).

Body Composition

A GE Lunar iDXA (GE Healthcare, Little Chalfont, United Kingdom) was used

to estimate lean body mass, body fat, distribution of body fat, and visceral adipose tissue.

Participants were scanned in supine with hips and forearms in neutral position. All metal

was removed prior to the scan.

Inter-Recti Distance and Muscle thickness

Characteristics of the anterior abdominal wall were assessed with a GE vivid e

ultrasound machine (8 LRS linear probe; GE Healthcare, Little Chalfont, United

Kingdom). Inter-recti distance was measured 4 cm above, 2.5 cm above, 2.5 cm below,

and 4 cm below the umbilicus, and thickness of the right rectus abdominis muscle belly

was measured at 2.5 cm above and below the umbilicus. Participants were positioned in

supine on a plinth (Beer, Schuster et al. 2009), and the measurement sites were identified

with a measuring tape and marked with marker. Images were taken at end expiration

with recommended transducer orientation (Teyhen, Gill et al. 2007). For IRD, three

images were obtained at each site and averaged. For muscle thickness, the largest

measurement was used. Images were excluded from analysis if the muscular borders

were not clearly defined. For women whose IRD exceeded the viewing range of the

transducer, the maximal width of the transducer viewing rage (3.85 cm) was recorded.

Experimental pain perception.

Pressure pain thresholds were assessed at the nailbed of the left middle finger and

at the lower abdomen (2 finger widths above pubic symphysis in control women and

women who experienced vaginal delivery, midpoint of Pfannenstiel incision for women

who had a Cesarean delivery) using a computerized pressure algometer (AlgoMed,

Medoc Ltd, Yishai, Israel). Participants were provided with a patient control button and

instructed to press the button as soon as they would rate pain above a zero on a zero to

ten pain scale. Pressure was applied at a rate of 10 KPa/s. Three trials were performed at

each site with an inter-stimulus interval of ten seconds. Pressure pain thresholds for the

three trials were averaged.

Statistical Analysis

Data within the text and tables are presented as means ± standard deviation (SD)

and in figures as means ± standard error of the mean (SEM). Subject characteristics (age,

height, weight, body composition), ASLR time-to-task failure, six-minute walk test

performance, pressure pain thresholds, physical activity (self-reported and accelerometer), inter-recti distance at each position, and rectus abdominis muscle thickness were compared between control and postpartum women with independent samples t-tests. Inter-recti distance across positions was analyzed with repeated measures analysis of variance (ANOVA) with group (control or postpartum) as the between-subjects factor. Nonparametric tests were used to compare MMT strength grades (Mann-Whitney U), questionnaire results (Mann-Whitney U) and ASLR test outcome (Chi-square) between groups. Spearman's Rho nonparametric correlation was used to test associations between variables that (1) were not ordinal level data (such as MMT), (2) did not demonstrate a linear relationship (such as IRD), or (3) were not normally distributed.

Impact of delivery type (vaginal vs Cesarean) was assessed for subject characteristics, ASLR time-to-task failure, physical function test performance, pressure pain thresholds, physical activity (self-reported and accelerometer), and rectus abdominis muscle thickness with independent samples t-tests. Inter-recti distance across positions was analyzed with repeated measures ANOVA with delivery type as between subjects factor. Nonparametric tests, as described above, were used to compare MMT strength grades, questionnaire results and ASLR test outcome between delivery types.

In a subgroup of participants (16 control women, 22 postpartum women [15 vaginal delivery]), the effect of time was assessed by comparing dependent variables at each time point (8 weeks and 26 weeks postpartum). For scale level data, paired samples t-tests were performed. For ordinal level data, or data that was not normally distributed, Wilcoxon rank signed test was performed.

Results

Participants. Twenty-three control women and 27 postpartum women (vaginal delivery n=17, Cesarean delivery n=10) completed testing at the initial (8 weeks postpartum) time point. Sixteen control women and 26 postpartum women (vaginal delivery n=16, Cesarean delivery n=10) completed testing at the follow up time point (26 weeks postpartum). Seven control women, two women from the vaginal delivery group, and three women from the Cesarean delivery group were lost to follow up due to schedule conflicts. Two women from the Cesarean delivery group and one woman from the vaginal delivery group completed testing only at the 24-26 week time point.

Descriptive data. Subject characteristics, including height, weight, rectus abdominis muscle thickness, and inter-recti distance, are presented for controls vs postpartum women in Table 4.1 and for vaginal delivery group vs Cesarean delivery group in Table 4.2. Results for clinical assessments, including ASLR test and questionnaires, are presented for postpartum vs control in Table 4.3 and for vaginal delivery vs Cesarean delivery in Table 4.4.

Table 4.1. Control vs Postpartum Subject Characteristics.

	INITIAL (8-10 wks postpartum)		FOLLOW UP (24-26 wks postpartum)	
	Control (n=23)	Postpartum (n=27)	Control (n=16)	Postpartum (n=26)
Age (yrs)	26.7 ± 9.9	31.3 ± 5.4*	25.4 ± 5.8	32.1 ± 5.3*
Weight (kg)	64.5 ± 11	75.1 ± 13.2*	63.4 ± 7.5	71.5 ± 14.6*
Height (cm)	166.6 ± 8.4	164.3 ± 4.8	166.4 ± 8.1	164.1 ± 4.8
BMI (kg/m^2)	23.1 ± 3.4	27.9 ± 4.9*	22.8 ± 2.1	26.9 ± 5.3*
Body Fat %	32.2 ± 5.4	38.9 ± 6.5*	32.7 ± 5.1	36.8 ± 8.6
RA muscle thickness (2.5 cm above umbilicus) (cm)	1.0 ± 0.2	0.8 ± 0.2*	1.0 ± 0.1	0.8 ± 0.1*
RA muscle thickness (2.5 cm below umbilicus) (cm)	1.0 ± 0.2	0.8 ± 0.2*	0.9 ± 0.1	0.8 ± 0.2
IRD 4 cm above umbilicus (cm)	1.1 ± 0.4	2.3 ± 1.1 (n=22)*	1.1 ± 0.6	2.3 ± 1.0 (n=25)*
IRD 2.5 cm above umbilicus (cm)	1.1 ± 0.4	2.5 ± 1.1 (n=21)*	1.0 ± 0.5	2.4 ± 1.0 (n=24)*
IRD 2.5 cm below umbilicus (cm)	0.5 ± 0.2	1.8 ± 0.9 (n=19)*	0.5 ± 0.2 (n=15)	2.0 ± 1.0 (n=21)*
IRD 4 cm below umbilicus (cm)	0.4 ± 0.2	1.5 ± 1.1 (n=22)*	0.3 ± 0.2	1.4 ± 1.1 (n=23)*
Average minutes/day of moderate intensity physical activity	37.9 ± 23.2 (n=18)	16.2 ± 15.5 (n=19)*	29.3 ± 14.1 (n=8)	16.7 ± 10.5 (n=13)*

| Self-reported physical activity over the previous 12 months (MET·hours·week^{-1}) | 41.2 ± 28.4 (n=22) | 20.7 ± 18.9 (n=25)* | 33.6 ± 24.3 (n=15) | 12.0 ± 9.8 (n=23)* |

Wks=weeks; yrs=years; kg=kilogram; cm=centimeter; m=meter; RA=rectus abdominis; IRD=inter-recti distance; MET=metabolic equivalents

Table 4.2. Cesarean vs Vaginal Delivery Subject Characteristics.

	8-10 wks postpartum		24-26 wks postpartum	
	Vaginal Delivery (n=17)	**Cesarean Delivery (n=10)**	**Vaginal Delivery (n=16)**	**Cesarean Delivery (n=10)**
Age (yrs)	30.6 ± 6.2	32.5 ± 3.6	31.3 ± 6.0	33.3 ± 4.0
Weeks Postpartum (Session 1)	8.6 ± 1.0	8.6 ± 0.4	25.3 ± 1.6	25.1 ± 0.7
Weeks Postpartum (Session 2)	9.4 ± 1.2	9.4 ± 0.5	26.1 ± 1.7	26.2 ± 0.6
Duration of pregnancy (weeks)	39.3 ± 1.0 (n=13)	38.0 ± 1.2* (n=9)	39.3 ± 1.1 (n=12)	38.3 ± 1.4
Fundal height prior to delivery (cm)	38.7 ± 1.3 (n=6)	37.0 ± 1.2 (n=5)	38.7 ± 1.3 (n=7)	37.0 ± 1.2*
Total Number of pregnancies	2.2 ± 1.2 (n=16)	3.2 ± 1.9 (n=9)	2.1 ± 1.1	3.0 ± 2.1
Weight (kg)	74.5 ± 14.8	76.2 ± 10.7	70.8 ± 15.8	72.7 ± 13.0
Height (cm)	164.8 ± 4.3	163.3 ± 5.6	165.4 ± 4.6	162.1 ± 4.8
BMI (kg/m^2)	27.5 ± 5.6	28.6 ± 3.7	26.3 ± 5.8	27.7 ± 4.5
Body Fat %	38.8 ± 7.2	39.1 ± 5.5	36.5 ± 8.9	37.5 ± 8.6
RA muscle thickness (2.5 cm above umbilicus) (cm)	0.8 ± 0.2	0.8 ± 0.1	0.8 ± 0.2	0.8 ± 0.1
RA muscle thickness (2.5 cm below umbilicus) (cm)	0.8 ± 0.2	0.8 ± 0.2	0.8 ± 0.2	0.8 ± 0.2
IRD 4 cm above umbilicus (cm)	2.5 ± 1.2 (n=16)	1.9 ± 0.7 (n=6)	2.3 ± 1.1	2.3 ± 0.9
IRD 2.5 cm above umbilicus (cm)	2.7 ± 1.1 (n=16)	2.0 ± 1.0 (n=5)	2.4 ± 1.1 (n=15)	2.4 ± 0.7 (n=9)
IRD 2.5 cm below umbilicus (cm)	1.8 ± 0.9 (n=15)	1.6 ± 1.2 (n=4)	1.9 ± 0.9 (n=16)	2.1 ± 1.3 (n=5)

IRD 4 cm below umbilicus (cm)	1.3 ± 1.1 (n=16)	2.0 ± 1.2 (n=6)	1.2 ± 1.1	1.7 ± 1.3
Average minutes/day of moderate intensity physical activity	17.1 ± 19.1 (n=10)	15.3 ± 11.2 (n=9)	17.0 ± 11.9	16.0 ± 7.8
Self-reported physical activity over the previous 12 months (MET·hours·week^{-1})	21.4 ± 16.6 (n=16)	19.4 ± 23.4 (n=9)	10.4 ± 8.1	14.4 ± 12.0

Wks=weeks; yrs=years; kg=kilogram; cm=centimeter; m=meter; RA=rectus abdominis; IRD=inter-recti distance; MET=metabolic equivalents

Clinical Measures of Abdominal Muscle Function

Manual Muscle Testing. Postpartum women demonstrated lower MMT strength grades than control women at 8 and 26 weeks postpartum ($p<0.001$, Table 4.3). There was no difference in MMT strength grades between women in the vaginal delivery and Cesarean delivery groups at 8 weeks or 26 weeks postpartum ($p=0.115$ and $p=0.397$, respectively, Table 4.4).

Active Straight Leg Raise Test. At the initial testing time point, 23% of control women and 37% of postpartum women had a positive ASLR test ($p = 0.280$, Table 4.3). Of the women who had positive ASLR tests, 40% of the postpartum women were positive bilaterally, and 20% of the control women had a positive ASLR test bilaterally. At follow up, 12.5% of the control women and 44% of the postpartum women tested positive for impaired lumbopelvic stability ($p = 0.035$, Table 4.3). Fifty-five percent of the positive ASLR tests in the postpartum group were bilateral positives, while no control women had a bilateral positive ASLR test at the follow up time point.

At 8 weeks postpartum, 41% of women who had a vaginal delivery and 30% of women who had a Cesarean delivery were positive for lumbopelvic instability ($p=0.692$,

Table 4.4). In the vaginal delivery group, 43% of the women with a positive ASLR test were positive bilaterally, and 33% of the women in the Cesarean group with a positive ASLR test had bilateral instability. At 26 weeks postpartum, 44% of both the women in the vaginal delivery group and the Cesarean delivery group had bilateral positive ASLR tests (p=1.00, Table 4.4). Of the women in the vaginal delivery group with a positive ASLR test, 57% had a positive test bilaterally. Fifty percent of the women in the Cesarean group with a positive ASLR test were positive bilaterally.

Table 4.3. Postpartum vs Control Clinical Assessments.

	INITIAL (8-10 wks PP)		FOLLOW UP (24-26 wks PP)	
	Control (n=23)	Postpartum (n=29)	Control (n=15)	Postpartum (n=26)
MMT (AU)	4.3 ± 1.0	2.7 ± 1.2*	4.5 ± 0.7	2.9 ± 1.1*
(+) ASLR test (% of subjects tested)	23%	37%	12.5%	44%*
Unilateral (+)	18.20%	22%	12.50%	20%
Bilateral (+)	4.50%	15%	0.00%	24%
(-) ASLR test (% of subjects tested)	77%	23%	87.5%	56%
Oswestry (% disability)	1.7 ± 3.2	4.6 ± 5.4*	0.8 ± 1.8	5.0 ± 7.2*
FABQ (AU)	3.9 ± 10.3	8.5 ± 10.5	0.5 ± 1.3	8.2 ± 12.2*
PFDI (AU)	8.2 ± 17.6 (n=10)	38.6 ± 42.6* (n=24)	6.1 ± 12.2 (n=4)	28.7 ± 24.7* (n=26)
PGQ (AU)	0.4 ± 1.3 (n=10)	4.4 ± 6.9* (n=23)	0 (n=4)	3.3 ± 6.2 (n=26)
Pelvic Pain & urgency/frequency (AU)	2.7 ± 2.5	3.4 ± 2.6 (n=27)	1.7 ± 1.6	3.4 ± 3.3
PSQI (AU)	4.0 ± 2.0 (n=22)	8.2 ± 2.8*	4.5 ± 2.3	7.4 ± 2.9*
PCS (AU)	9.7 ± 7.3	10.9 ± 9.8	5.8 ± 6.0	9.2 ± 9.5

| 6MWT (m) | 689 ± 57 | 640 ± 65* | 692.5 ± 56.1 | 648.7 ± 61.4* |

AU=Arbitrary Units; FABQ=Fear Avoidance Beliefs Questionnaire; PFDI=Pelvic Floor Distress Inventory; PGQ=Pelvic Girdle Questionnaire; PSQI=Pittsburgh Sleep Quality Questionnaire; PCS=Pain Catastrophizing Scale; 6MWT=Six Minute Walk Test

**Table 4.4. Cesarean vs Vaginal Delivery Clinical Assessments.**

	INITIAL (8-10 wks PP)		FOLLOW UP (24-26 wks PP)	
	Vaginal Delivery (n=18)	Cesarean Delivery (n=11)	Vaginal Delivery (n=17)	Cesarean Delivery (n=11)
MMT (AU)	2.9 ± 1.1	2.4 ± 1.4	3.0 ± 1.1	2.7 ± 1.2
(+) ASLR test (% of subjects tested)	41%	30%	44%	44%
Unilateral (+)	23.50%	20%	19.00%	22%
Bilateral (+)	17.60%	10%	25.00%	22%
(-) ASLR test (% of subjects tested)	59%	70%	56%	56%
Oswestry (% disability)	6.4 ± 6.0	1.6 ± 2.5*	5.8 ± 8.0	3.9 ± 6.1
FABQ (AU)	9.1 ± 9.7	7.5 ± 12.1	9.0 ± 11.2	6.8 ± 14.2
PFDI (AU)	43.8 ± 34.0	30.9 ± 49.8*	30.7 ± 27.5	25.4 ± 20.3
PGQ (AU)	7.3 ± 8.6	1.4 ± 2.8*	2.2 ± 4.9	5.1 ± 7.8
Pelvic Pain & urgency/frequency	2.9 ± 1.9	4.1 ± 3.5	2.3 ± 1.8	5.3 ± 4.3
PSQI (AU)	8.2 ± 2.4	8.1 ± 3.4	6.9 ± 3.0	8.2 ± 2.7
PCS (AU)	12.3 ± 10.0	8.7 ± 9.6	10.3 ± 7.7	7.4 ± 12.0
PP Depression (AU)	4.4 ± 3.5	2.5 ± 2.8	4.3 ± 3.5	5.0 ± 4.3
6MWT (m)	645 ± 62.0	631.8 ± 71.3	655.6 ± 53.2	637.6 ± 74.5

AU=Arbitrary Units; FABQ=Fear Avoidance Beliefs Questionnaire; PFDI=Pelvic Floor Distress Inventory; PGQ=Pelvic Girdle Questionnaire; PSQI=Pittsburgh Sleep Quality Questionnaire; PCS=Pain Catastrophizing Scale; PP Depression=Edinburgh Postnatal Depression Questionnaire; 6MWT=Six Minute Walk Test

Active Straight Leg Raise Fatigue Task. Postpartum women at 8 weeks had a shorter time-to-task failure (more fatigable) than control women (109 ± 50 s vs 165 ± 66 s, $p = 0.001$) and this persisted at 26 weeks postpartum (125 ± 45 s vs 163 ± 63 s, $p = 0.028$; Figure 4.1A). There was no difference in time-to-task failure between delivery types at 8 weeks (114 ± 52 s vaginal vs 101 ± 49 s Cesarean, $p = 0.512$) or 26 weeks postpartum (113 ± 38 s vaginal vs 144 ± 50 s Cesarean, $p = 0.086$; Figure 4.1B).

Subjects were also grouped by ASLR test status (positive vs negative test). No difference in time-to-task failure was observed between women with a positive ASLR test and women with a negative ASLR test at the initial (126 ± 47 s vs 142 ± 69 s, $p = 0.431$) or follow up (123 ± 52 s vs 147 ± 56 s, $p = 0.179$; Figure 4.1C) time points.

Paired samples t-tests revealed that no group demonstrated a change in ASLR time-to-task failure from one time point to the next (Control $p = 0.843$, Postpartum $p = 0.735$, Vaginal $p = 0.807$, Cesarean $p = 0.310$).

Figure 4.1. ASLR Fatigability
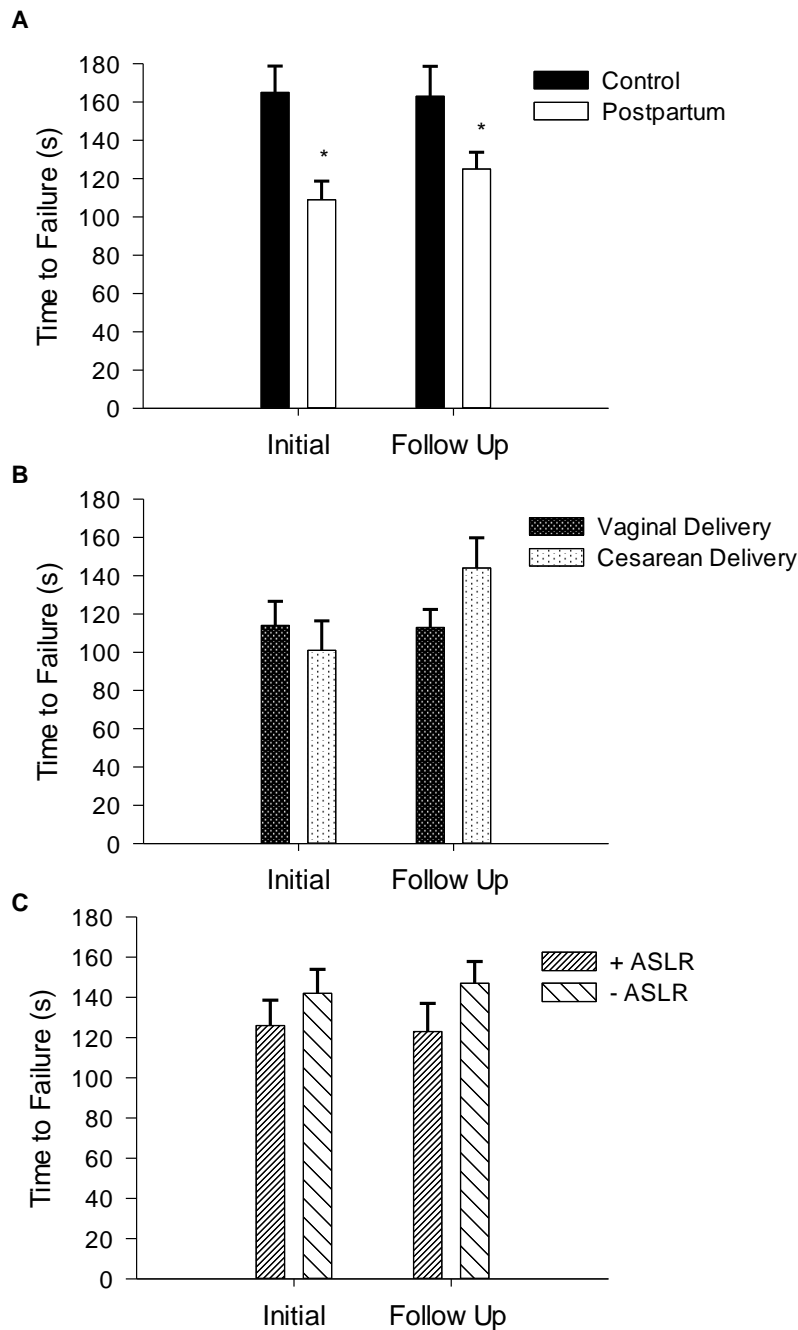
Figure 4.1. Fatigability of the lumbopelvic stabilizing muscles at both time points (8 weeks [initial] and 26 weeks [follow up] postpartum) using the newly developed ASLR fatigue task. Postpartum women demonstrate greater fatigability (shorter time-to-task failure) than control women at both time points (A), with no difference between women who had a vaginal delivery and women who had a Cesarean delivery (B). Women with a positive ASLR test, suggesting lumbopelvic instability, did not differ in time-to-task failure compared to women with a negative ASLR test (C).
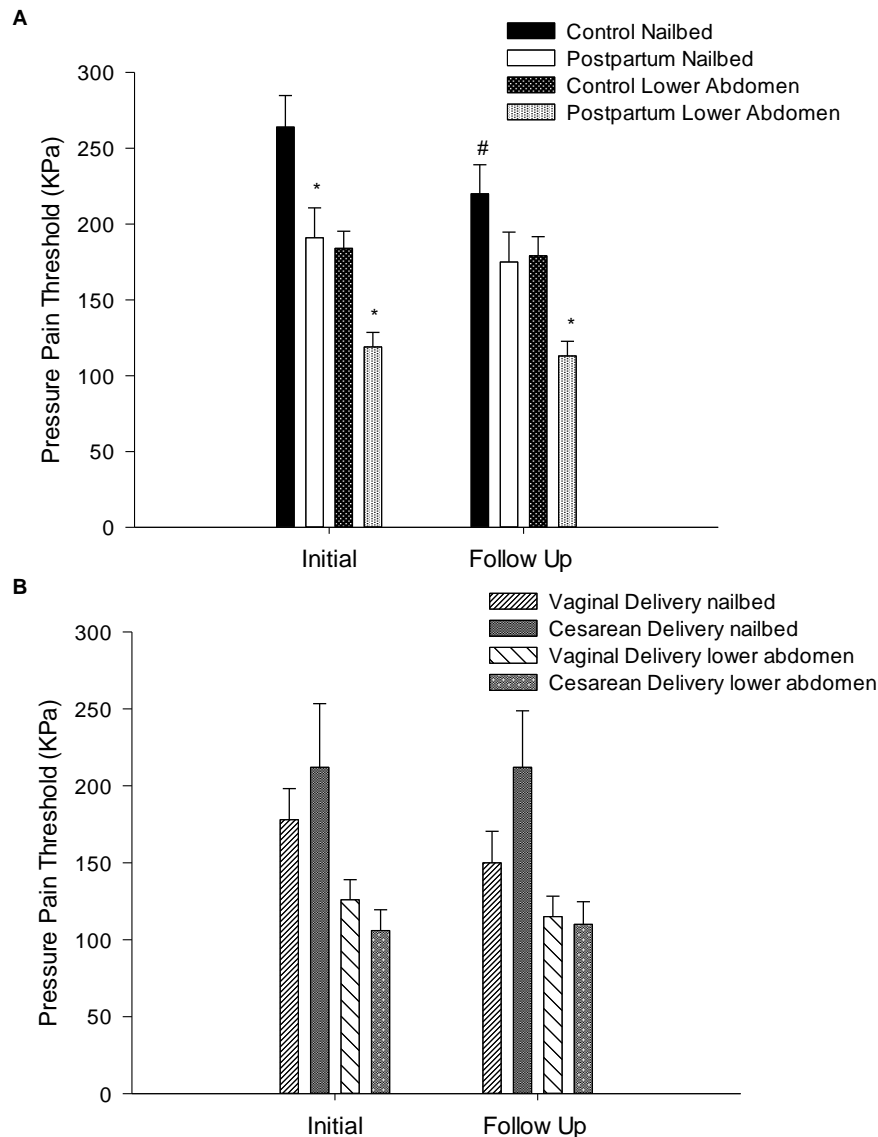
Experimental Pain Perception

At 8 weeks, postpartum women were more sensitive to pain (lower pressure pain threshold) at the nailbed than control women (191 ± 102 KPa vs 264 ± 98 KPa, respectively, $p = 0.015$) and the lower abdomen (119 ± 50 KPa vs 184 ± 54 KPa, respectively, $p < 0.001$). At 26 weeks postpartum, pressure pain threshold at the nailbed was not different than control women (175 ± 98 KPa vs 220 ± 72 KPa, respectively, $p = 0.141$), but postpartum women remained more sensitive to pain at the lower abdomen (113 ± 49 KPa vs 180 ± 48 KPa, respectively, $p < 0.001$; Figure 4.2A).

There was no difference in pressure pain thresholds at the nailbed between delivery types at 8 weeks postpartum (178 ± 83 KPa vaginal vs 212 ± 131 KPa Cesarean, $p = 0.480$) or 26 weeks postpartum (150 ± 79 KPa vaginal vs 212 ± 116 KPa Cesarean, $p = 0.120$). Pressure pain thresholds at the lower abdomen were similar between delivery types at 8 weeks (126 ± 53 KPa vaginal vs 106 ± 43 KPa Cesarean, $p = 0.326$) and 26 weeks (115 ± 52 KPa vaginal vs 110 ± 47 KPa Cesarean, $p = 0.826$; Figure 4.2B) postpartum.

Participants were again grouped by ASLR test result (positive vs negative). Pressure pain thresholds were similar between groups at the initial time point for both the nailbed (228 ± 94.5 KPa positive vs 218.4 ± 101.9 KPa negative, $p = 0.759$) and the lower abdomen (145 ± 40.4 KPa positive vs 148 ± 68.8 KPa negative, $p = 0.889$). At the follow up time point, women with a positive ASLR test had lower pressure pain thresholds at the nailbed (148 ± 68.9 KPa vs 214 ± 96.4 KPa, $p = 0.035$) and lower

abdomen (107 ± 42.8 KPa vs 152 ± 59.5 KPa, $p=0.019$; Figure 4.2C) than women with a negative ASLR test.

Control women demonstrated a decline in pressure pain threshold at the nailbed between the initial and follow up testing ($p=0.047$), but no difference in pressure pain threshold at the abdomen ($p=0.542$). Postpartum women did not demonstrate a change in pressure pain threshold at the nailbed (postpartum grouped $p=0.269$; vaginal $p=0.176$; Cesarean $p=0.866$) or lower abdomen (postpartum grouped $p=0.734$; vaginal $p=0.199$; Cesarean $p=0.179$).

Figure 4.2. Pressure Pain Thresholds

Figure 4.2. Postpartum women were more sensitive to pain (lower pressure pain threshold [PPT]) than control women at both the nailbed and the lower abdomen at 8 weeks postpartum (A). By 26 weeks, postpartum women had a similar PPT as control women at the nailbed, but continued to demonstrate heightened sensitivity to pain at the lower abdomen (A). There were no differences in pain sensitivity between delivery types (vaginal vs Cesarean) at either body site at 8 weeks or 26 weeks postpartum (B).

Associations

Performance on the ASLR Fatigue Task was associated, at both time points, with body composition, inter-recti distance, pain sensitivity, rectus abdominis muscle thickness, self-reported physical activity over the previous year, and manual muscle testing. Shorter time-to-task failure was associated with higher body fat percentage (8 weeks: r = -0.601, $p < 0.001$, Figure 4.3A; 26 weeks: r = -0.468, $p = 0.002$, Figure 4.3B). Women with a greater inter-recti distance 2.5 cm below the umbilicus had a shorter time-to-task failure (8 weeks: r = -0.443, $p = 0.003$, Figure 4.3C; 26 weeks: r = -0.508, $p = 0.002$; Figure 4.3D). Thinner rectus abdominis muscle belly at 2.5 cm above the umbilicus was also associated with greater fatigability (8 weeks: r = 0.332, $p = 0.018$, Figure 4.3E; 26 weeks: r = 0.404, $p = 0.010$; Figure 4.3F). Women who walked a shorter distance in six minutes were also more fatigable at 8 weeks postpartum (8 weeks: r = 0.451, $p = 0.001$, Figure 4.4A) although this did not reach significance at 26 weeks (r = 0.307, $p = 0.051$; Figure 4.4B). Lower self-reported physical activity over the previous year was associated with a shorter time-to-task failure on the ASLR fatigue task (8 weeks: r = 0.345, $p = 0.017$, Figure 4.4C; 26 weeks: r = 0.376, $p = 0.020$, Figure 4.4D), as were lower pressure pain threshold at the lower abdomen (8 weeks: r = 0.407, $p = 0.003$, Figure 4.4E; 26 weeks: r = 0.375, $p = 0.020$, Figure 4.4F), and lower manual muscle testing strength grade (8 weeks: r = 0.532, $p < 0.001$; 26 weeks: r = 0.360, $p = 0.026$).

Performance on the ASLR fatigue task was not correlated with time-to-task failure on the intermittent isometric trunk flexion fatiguing exercise task at 8 weeks (r = 0.297, *p* = 0.056) or 26 weeks (r = 0.288, *p* = 0.071).

Figure 4.3. Associations
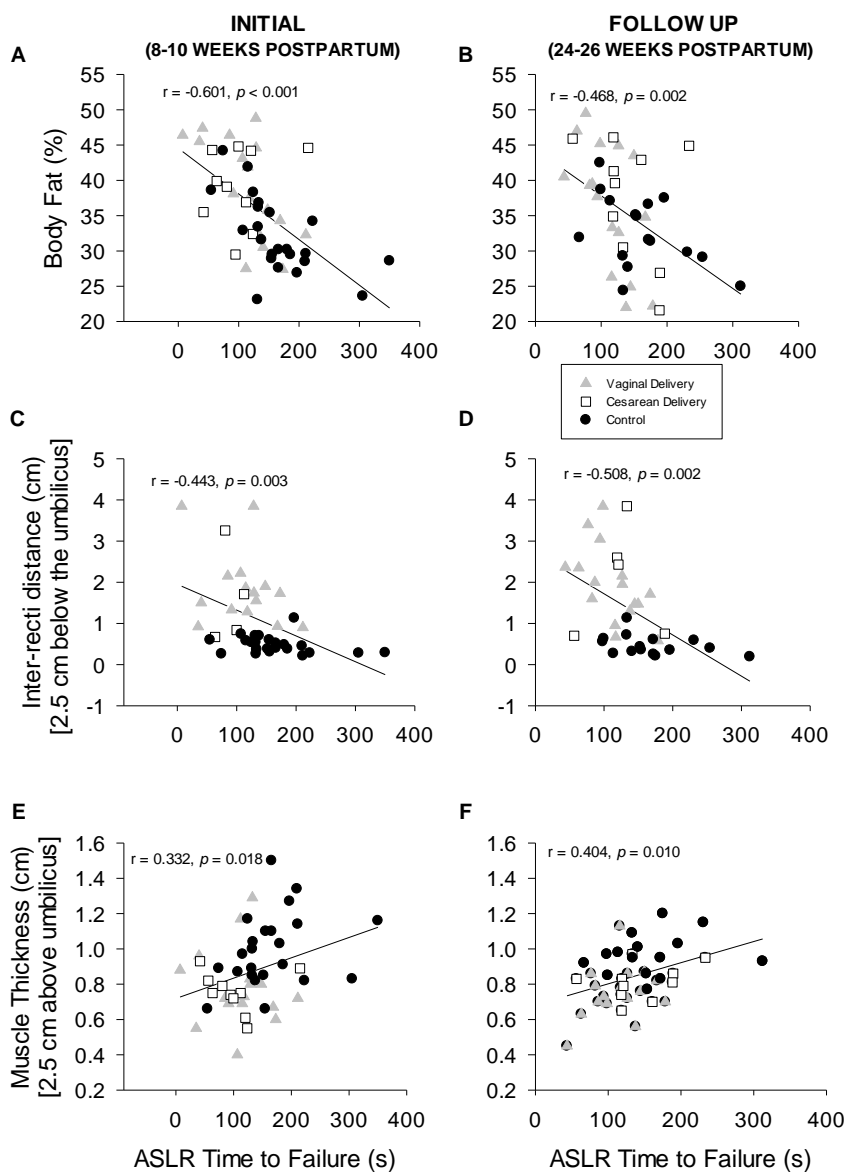
Figure 4.3. Longer time-to-task failure on the ASLR fatigue task was associated at both time points with lower body fat (A & B), smaller inter-recti distance (C & D), and thicker rectus abdominis muscle (E & F).

Figure 4.4. Associations
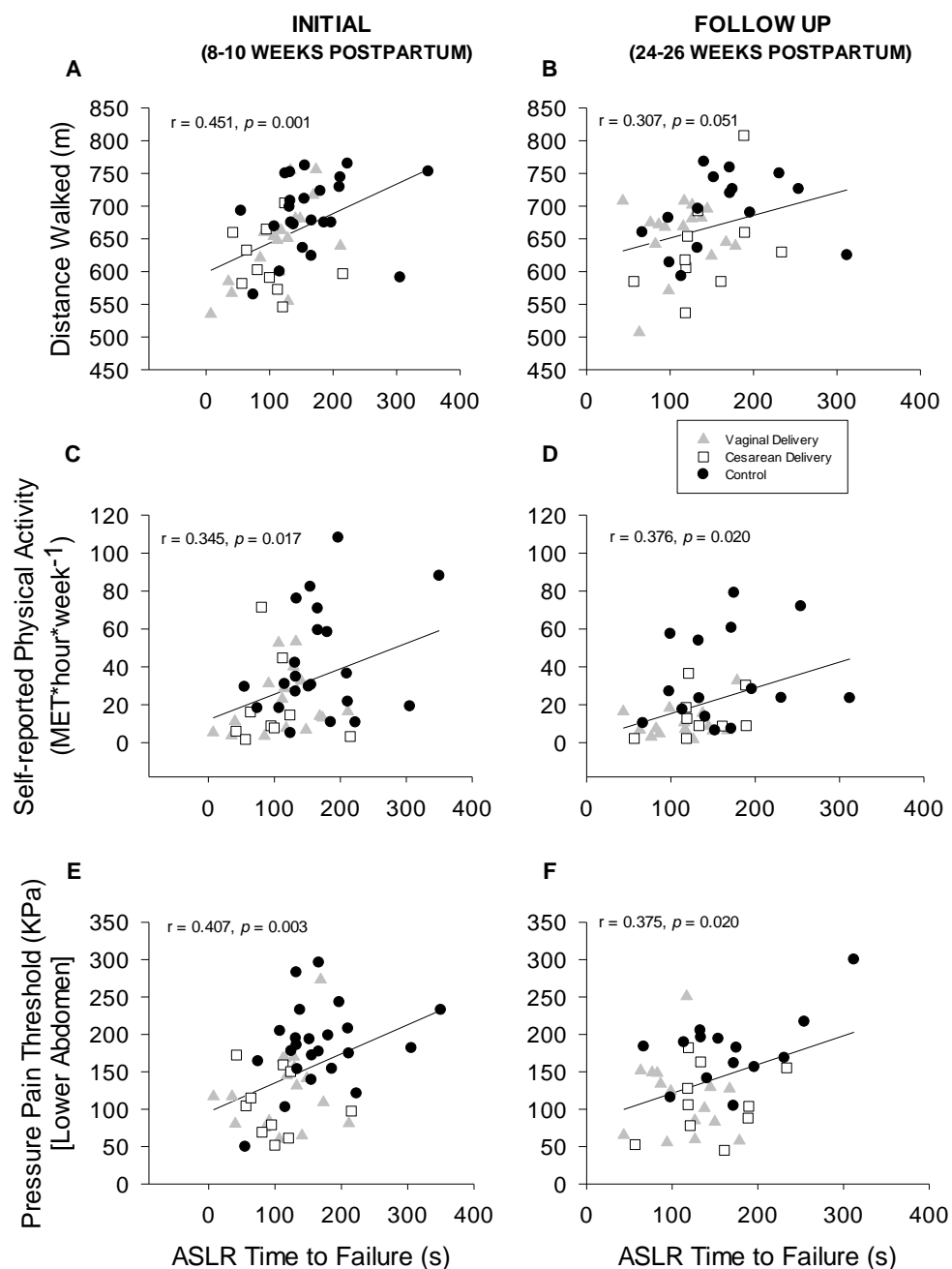
Figure 4.4 Longer time-to-task failure on the ASLR fatigue task was associated at both time points with greater distance walked in six minutes (A & B), greater self-reported physical activity over the previous year (C & D), and higher pressure pain threshold at the lower abdomen (E & F).

Discussion

The novel finding of this study is that postpartum women demonstrated significant deficits in fatigability of the lumbopelvic stabilizing muscles, up to 26 weeks after childbirth, as assessed by the newly-developed ASLR Fatigue Task. The greater fatigability of the postpartum women was independent of lumbopelvic stability, as no difference in time-to-task failure was noted between women who had a positive ASLR test and women who had a negative ASLR test. Women who reported greater physical activity over the preceding year and who had lower body fat, smaller inter-recti distance, a thicker rectus abdominis muscle, and a higher manual muscle testing strength grade performed best on the ASLR Fatigue Task. Women with a short time-to-task failure also demonstrated greater sensitivity to pain at the lower abdomen. Women with lumbopelvic instability, as evidenced by a positive ASLR test, also demonstrated greater sensitivity to pain than women with a negative ASLR test.

This is the first study to establish the ASLR Fatigue Task as a possible clinical measure of fatigability of the lumbopelvic stabilizing muscles. This test showed that postpartum women are more fatigable than women who have never been pregnant, and that this increased fatigability was still present approximately 6 months after childbirth. The finding of increased fatigability in postpartum women is consistent with findings in Chapter 3 that showed greater fatigability of trunk flexor muscles for an intermittent, isometric trunk flexion fatiguing task in the Biodex dynamometer. While the differences in fatigability between postpartum and control women (34% at 8 weeks postpartum, 23% at 26 weeks postpartum) for the ASLR fatigue task are significant, they are not as

profound as the deficits in trunk flexor fatigability measured in the Biodex dynamometer (71% at 8 weeks, 52% at 26 weeks). Time-to-task failure for the ASLR fatigue task was also significantly lower for both controls and postpartum women than demonstrated with the trunk flexor fatigue task at initial (165 ± 66 s vs 644 ± 327 s Control; 109 ± 50 s vs 189 ± 156 s Postpartum). It is expected that the ASLR fatigue task would have a shorter time-to-task failure than the Biodex fatigue task because the ASLR fatigue task is a sustained task, which compromises blood flow, while the Biodex fatigue task was intermittent, which allows periods of muscle perfusion and clearance of metabolic byproducts (Hunter, Critchlow et al. 2004, Hunter, Critchlow et al. 2004, Enoka and Duchateau 2008, Hunter 2014, Keller-Ross, Pereira et al. 2014). The two tests also assess different functions of the abdominal muscles (lumbopelvic stabilization vs thoracolumbar flexion), and thus target different muscles within the abdominal muscle group: the ASLR fatigue task is more representative of the function of the transverse abdominis, while the trunk flexion tasks are representative of the rectus abdominis and bilateral internal and external oblique muscles. The shorter time-to-task failure of the ASLR fatigue task, along with the fact that it requires minimal additional equipment (pressure biofeedback unit, stopwatch), makes it a more ideal test for clinical use.

Performance on the ASLR fatigue task was also associated with manual muscle testing strength grade. Postpartum women were weaker than control women when assessed with MMT at 8 weeks and 26 weeks postpartum, which is consistent with a previous study from our group that demonstrated lower isometric trunk flexion strength in postpartum women using the Biodex dynamometer (Chapter 3). However, in the current study, there was no change in MMT strength grade across time for postpartum

women, while our previous work actually showed a decline in maximal voluntary trunk flexion strength at 26 weeks in postpartum women, driven by a decline in strength of women who experienced a vaginal birth (Chapter 3). This suggests that manual muscle testing may not be sensitive enough to detect subtle changes in strength across time. Thus, the ASLR fatigue task may be a more sensitive screening tool than MMT for clinical use to determine change in function over time.

Fatigability of the lumbopelvic stabilizing muscles was also associated with inter-recti distance. Inter-recti distance did not change for control women, the postpartum group as a whole, or women who experienced a vaginal delivery. The Cesarean delivery group did demonstrate a decrease in inter-recti distance at 4 cm below the umbilicus at the 26 week time point; however, inter-recti distance in this group remained wider than controls and was similar to women in the vaginal delivery. The association between fatigability and IRD may be partially explained by an impaired ability of the anterior abdominal wall fascia to transfer muscularly generated forces (Brown and McGill 2009). The thinning of the connective tissue caused by pregnancy hormones and substantial stretch of the abdominal wall may compromise the integrity of the fascia, and some of the force generated by the abdominal muscles may be "lost" in this incompetent tissue. Gracovetsky (2008) proposed a theory of the importance of fascia in muscle fatigability and spinal stability, using the lumbodorsal fascia as an example (Gracovetsky 2008), based on a mathematical model of the lumbar spine (Gracovetsky, Farfan et al. 1977). Because fascia is viscoelastic, and thus stretches, it is impossible to load it in a continuous manner. Gracovetsky (2008) suggests that muscles employ an oscillatory activation pattern to cyclically load and unload the collagen structures, which in turn

prolongs the amount of time the muscle is capable of performing a motor task by utilizing these short "rest" periods during the unloading phase (Gracovetsky, Farfan et al. 1977, Gracovetsky 2008). It is possible that the anterior abdominal fascia, already stretched and thinned from pregnancy, has different viscoelastic properties than the fascia of a nulligravid woman, thus requiring greater muscular effort to appropriately load the tissue for successful completion of motor tasks, leading to greater fatigability in postpartum women.

Postpartum women were more sensitive to pain than control women, especially at the abdomen, up to 26 weeks postpartum. The increased sensitivity to pain exhibited by the postpartum women at the nailbed at the 8-week postpartum time point indicates possible central mechanisms at play (Graven-Nielsen and Arendt-Nielsen 2002, Woolf 2011). The lack of a difference in pressure pain thresholds at the nailbed between control and postpartum women at 26 weeks is driven by a decline in PPT in the control group. This may be due to a learning effect in the control women. However, it does not definitively rule out the presence of continued central mechanisms being responsible for altered pain perception in the postpartum women, who experienced no change in PPT at the nailbed between 8 and 26 weeks. The lower pressure pain thresholds at the lower abdomen observed in the postpartum women as compared to control women also suggest some local changes, such as increased nociceptor sensitivity, that may contribute to heightened pain sensitivity in this group (Graven-Nielsen and Arendt-Nielsen 2002).

Postpartum women in this study demonstrated worse scores than control women on several questionnaires regarding muscular function, pain, and disability. While postpartum women demonstrated Oswestry and FABQ scores that were statistically

higher than control women, these results were not clinically significant. Further investigation of the fatigability of the lumbopelvic stabilizing muscles in women (postpartum and nulligravid) with clinically significant Oswestry scores would be beneficial to the understanding of the role of fatigability of this muscle group with low back pain and disability. Postpartum women also demonstrated impaired sleep quality, pelvic floor function, and increased pelvic girdle symptoms as compared to control women. While women in the vaginal delivery group had higher Oswestry, PFDI, and PGQ scores than women in the Cesarean delivery group at 8 weeks postpartum, no difference in these questionnaires was observed between delivery types at 26 weeks postpartum. This lack of difference at 26 weeks was driven by improvement in the vaginal delivery group, while scores for the Cesarean delivery group did not change across time. These findings suggest that vaginal birth is a risk factor for low back pain, pelvic floor dysfunction, and pelvic girdle pain only in the immediate postpartum period, which is in contrast to the popular opinion that Cesarean delivery is protective against these impairments (Bost 2000).

Fatigability of the lumbopelvic stabilizing muscles was also associated with total body fat, thickness of the rectus abdominis muscle, functional mobility, and self-reported physical activity over the preceding 12 months. This should be interpreted cautiously, especially at 8 weeks postpartum, as pregnancy facilitates fat storage in the mother to use as a fuel source during late pregnancy when blood glucose is prioritized to the fetus (Chearskul 2006), thus a higher body fat percentage may be physiologically "normal" in the immediate postpartum period. However, it appears that women who are able to reduce this excess body fat by 26 weeks postpartum are less fatigable than women whose

body fat percentage remains elevated. Thus, it may be more clinically relevant to assess changes in body fat rather than changes in weight after childbirth.

Women who were more fatigable during ASLR also walked a shorter distance in six minutes than those who were less fatigable. This association was strongest at the 8-week time point, and was only a trend (p = 0.051) at 26 weeks postpartum. The mechanism for this relationship is unknown at this time. It is possible that instability in the pelvic joints from pregnancy and childbirth, or impaired transfer of muscularly generated forces, contribute to decreased performance of functional mobility. It is also possible that cardiovascular fitness is lower in the postpartum group due to the changes in physical activity during pregnancy and immediately after childbirth, and this observation is supported by the self-reported and objectively measured lower physical activity in the postpartum group. The association between physical activity and ASLR fatigability has also been shown with the trunk flexor muscles using an intermittent, isometric fatiguing exercise protocol in healthy men and women (Deering, Senefeld et al. 2017) and postpartum women (Chapter 3). These findings support the importance of individualized, prescribed exercise to increase muscle mass and decrease body fat in the postpartum period.

Further research is needed to determine the impact of rehabilitation on fatigability of the lumbopelvic stabilizing muscles. The significantly increased fatigability in this group of rather high-functioning postpartum women also highlights the need to evaluate fatigability in postpartum women with clinically significant pain syndromes and musculoskeletal impairments (such as incontinence and pelvic organ prolapse).

V.   CONCLUSION

This dissertation examined the impact of pregnancy and method of childbirth on strength and fatigability of the abdominal muscles, as well as exploring abdominal muscle function in healthy men and healthy, nulligravid women. The abdominal muscles play an important role in stability of the lumbar spine and pelvis, maintenance of continence, and regulation of intra-abdominal pressure, and function of these muscles is linked to several pregnancy-related impairments, such as low back pain, pelvic girdle pain, and incontinence. Because the abdominal wall is subjected to significant perturbation during pregnancy (Boissonnault and Blaschak 1988, Kristiansson, Svardsudd et al. 1999, Chearskul 2006, Coldron, Stokes et al. 2008), and may be further compromised by Cesarean delivery (Corton, Leveno et al. 2009), it is surprising that the abdominal musculature is not objectively assessed as part of standard medical care (Borders 2006). As such, there is limited understanding of changes in abdominal muscle function following pregnancy and childbirth. This dissertation primarily examined maximal strength of the trunk flexor muscles and fatigability of the trunk flexor and lumbopelvic stabilizing muscles in order to quantify function of the abdominal muscles. This chapter summarizes and interprets the main findings of these studies, highlights their scientific and clinical significance, and provides suggestions for further investigation in future studies.

This dissertation established a new trunk flexion testing protocol, utilizing the Biodex dynamometer, to limit contribution of the hip flexor muscles to a trunk flexion task to better understand the function of the abdominal muscles. To establish the

experimental protocol, and to determine if sex differences exist in abdominal muscle function, study one examined trunk flexor strength, fatigability, and torque steadiness in healthy men and healthy, nulligravid women. The novel findings of this study included: (1) lack of a sex difference in fatigability and torque steadiness (torque fluctuations); (2) a positive relationship between maximal strength and fatigability; (3) a sex difference in the shape of the torque-angle curve, with men demonstrating greater torque than women in positions of trunk extensions, but no sex difference in strength in upright or flexed trunk positions; (4) torque fluctuations for both sexes were significantly higher in the trunk flexor muscles (~15%) than those typically observed in limb muscles (~1.5-4%) (Hunter, Critchlow et al. 2004, Tracy, Maluf et al. 2005, Welsh, Dinenno et al. 2007). The lack of a sex difference in fatigability and the positive association between strength and fatigability may both be partially explained by the fact that the abdominal muscles are important postural and stabilizing muscles, thus making fatigue resistance a necessity for both sexes. The large torque fluctuations observed during trunk flexion contractions may be influenced by several factors, including ventilation, the size of the trunk, and the neurological complexity involved with activating several large muscles. Further research into the mechanisms of trunk flexor fatigue and force control is needed to better understand the impact of these metrics of muscle function on low back injury and spinal stability.

The current method to assess abdominal function is certainly not without limitations. First, limiting hip flexor involvement required a significant amount of education, monitoring, and cueing of study participants to ensure proper technique. This was also challenging during the fatiguing exercise task, when contractions were separated

by only 4 seconds, and participants were receiving strong encouragement to continue the task as long as possible. Frequent reminders for proper technique and cueing to not utilize compensatory techniques (such as hip flexor involvement) were required for many participants. In addition to technique, the objective measurement of trunk flexion torque requires the use of significant equipment (in this case, the Biodex System 4 dynamometer and the back flexion/extension attachment) and time. This makes quantifying trunk flexor torque difficult in clinical settings where access to such equipment may not be possible and time is often limited. Further, this dissertation only examined abdominal muscle function during isometric contractions. It is possible that different results may be observed under conditions utilizing dynamic contractions.

Chapters 3 and 4 examined the impact of pregnancy and mode of delivery on trunk flexor strength and fatigability of the trunk flexor muscles and lumbopelvic stabilizing muscles, as well as experimental pain perception. These chapters also explored associations of abdominal muscle function and several other factors to provide insight into the mechanisms for any differences between groups, and also to determine the functional significance of the laboratory-based tests. These factors included muscle thickness, inter-recti distance, physical activity, and functional mobility. At 8 weeks after delivery, postpartum women demonstrated severe deficits in isometric voluntary strength (33%) and fatigability (71%) of the trunk flexor muscles (Chapter 3), and fatigability of the lumbopelvic stabilizing muscles (34%) (Chapter 4) compared to control women. Postpartum women were also more sensitive to an experimental pressure pain stimulus at the nailbed (26% more sensitive), lower abdomen (37%), and superior rectus abdominis (36%) (Chapter 4). These findings are alarming because many women who work outside

of the home have already returned to work by 8 weeks postpartum. For women who have jobs that involve heavy lifting, or repetitive lifting/carrying tasks, the profound deficits in strength and increased fatigability could put these women at increased risk of spinal injury. These findings also highlight a gap in women's healthcare practice: the current standard practice of care for postpartum women makes the assumption that when the smooth muscle of the uterus has recovered from pregnancy and childbirth, all body systems (including the musculoskeletal system) have recovered, as well. Incorporating assessment of the musculoskeletal system by healthcare professionals who are experts in musculoskeletal assessment, diagnosis, and rehabilitation (such as physiatrists and physical therapists) may improve musculoskeletal recovery in postpartum women.

Furthermore, the deficits in function were substantial at 6 months postpartum. At 26 weeks after delivery, postpartum women continued to demonstrate significant impairments in strength (44%) and fatigability (52%) of the trunk flexor muscles (Chapter 3), and fatigability of the lumbopelvic stabilizing muscles (23%) (Chapter 4) compared to control women. Postpartum women demonstrated a similar pressure pain threshold as control women at the nailbed, but continued to demonstrate increased sensitivity to experimental pain at the lower abdomen (37%) and superior rectus abdominis (30%) (Chapter 4). Postpartum deficits in fatigability of the lumbopelvic stabilizing muscles and trunk flexor muscles have not been previously reported and the large deficits in function even 6-months postpartum highlight that the neuromuscular function of this population is neglected.

In addition, this body of work established a new clinical measure of fatigability of the lumbopelvic stabilizing muscles that can be used in clinical populations and is able to

be performed in the clinic by health care professionals. Women with the greatest deficits in abdominal muscle function demonstrated thinner rectus abdominis muscle thickness, larger inter-recti distance, worse performance on the six-minute walk test, and lower physical activity levels than the women with the best abdominal muscle function. Postpartum women also demonstrated the positive association between trunk flexor strength and fatigability (Chapter 3) that was observed in men and nulligravid women (Chapter 2). These findings highlight the importance of skilled assessment and rehabilitation of the musculoskeletal system as standard medical care following pregnancy. Appropriate management of pain during and after pregnancy is also important, in order to reduce the likelihood of development of chronic pain syndromes.

This dissertation established that musculoskeletal function, especially of the abdominal muscles, is significantly impaired following pregnancy and childbirth. While these studies did explore some variables, such as physical activity, inter-recti distance, and body composition, that may be associated with abdominal muscle function, it did not directly test specific mechanisms that may be responsible for the profound impairments in strength and fatigability observed in postpartum women. Future research is needed to probe the neuromuscular system to identify the physiological mechanisms that are primarily responsible for decreased strength and increased fatigability of the abdominal muscles in postpartum women. For example, fMRI studies have identified alterations in neurotransmitters and neural circuitry in the brains of mothers (Kim, Strathearn et al. 2016). It is possible that these alterations may impact central mechanisms of fatigability in postpartum women, contributing to the greater fatigability of the trunk flexor muscles and lumbopelvic stabilizing muscles of postpartum women. It is also possible that the

mechanical stress (ie, stretch) experienced by the abdominal wall during pregnancy combined with the influence of systemically circulating pregnancy hormones can alter the contractile properties of the muscle fibers themselves, thus resulting in a greater contribution of peripheral mechanisms to the increased fatigability of the lumbopelvic stabilizing and trunk flexor muscles of postpartum women. A third hypothesis involves the dramatic changes to the connective tissue of the anterior abdominal wall. Animal studies (Brown and McGill 2009) and computer modeling studies (Gracovetsky, Farfan et al. 1977) have pointed to the importance of fascia for the transfer of muscularly generated forces and the distribution of forces to avoid overstressing of one structure as a means to decrease fatigability. If the fascia of the anterior abdominal wall is incompetent following pregnancy, and possibly further damaged by Cesarean delivery, it is possible that, even if the contractile tissue of the abdominal muscles is functioning appropriately, the force generated by the abdominal muscles may not be appropriately transferred to the skeletal system. Finally, future research into the impact of rehabilitation on muscular function in postpartum women is also warranted to establish the most effective treatment protocols.

BIBLIOGRAPHY

Albert, H., M. Godskesen and J. Westergaard (2000). "Evaluation of clinical tests used in classification procedures in pregnancy-related pelvic joint pain." Eur Spine J 9(2): 161-166.

Allen, D. G., G. D. Lamb and H. Westerblad (2008). "Skeletal muscle fatigue: cellular mechanisms." Physiol Rev 88(1): 287-332.

Almuklass, A. M., R. C. Price, J. R. Gould and R. M. Enoka (2016). "Force steadiness as a predictor of time to complete a pegboard test of dexterity in young men and women." J Appl Physiol (1985) 120(12): 1410-1417.

Andersson, E., J. Nilsson, Z. Ma and A. Thorstensson (1997). "Abdominal and hip flexor muscle activation during various training exercises." European Journal of Applied Physiology and Occupational Physiology 75(2): 115-123.

Archuleta, K. (2015). Handbook on Leave and Workplace Flexibilities for Childbirth, Adoption, and Foster Care. U. S. O. o. P. Management.

Arendt-Nielsen, L. and D. Yarnitsky (2009). "Experimental and clinical applications of quantitative sensory testing applied to skin, muscles and viscera." J Pain 10(6): 556-572.

Ashton-Miller, J. A. and J. O. Delancey (2009). "On the biomechanics of vaginal birth and common sequelae." Annu Rev Biomed Eng 11: 163-176.

Avin, K. G. and L. A. Law (2011). "Age-related differences in muscle fatigue vary by contraction type: a meta-analysis." Phys Ther 91(8): 1153-1165.

Barber, M. D., M. N. Kuchibhatla, C. F. Pieper and R. C. Bump (2001). "Psychometric evaluation of 2 comprehensive condition-specific quality of life instruments for women with pelvic floor disorders." Am J Obstet Gynecol 185(6): 1388-1395.

Bastiaenen, C., R. de Bie and G. Essed (2007). "Pregnancy-related pelvic girdle pain." Acta Obstetricia et Gynecologica Scandinavica 86: 1277-1279.

Beer, G. M., A. Schuster, B. Seifert, M. Manestar, D. Mihic-Probst and S. A. Weber (2009). "The Normal Width of the Linea Alba in Nulliparous Women." Clinical Anatomy 22(6): 706-711.

Bigland-Ritchie, B., F. Furbush and J. J. Woods (1986). "Fatigue of intermittent submaximal voluntary contractions: central and peripheral factors." J Appl Physiol (1985) 61(2): 421-429.

Bigland-Ritchie, B., D. A. Jones, G. P. Hosking and R. H. Edwards (1978). "Central and peripheral fatigue in sustained maximum voluntary contractions of human quadriceps muscle." Clin Sci Mol Med 54(6): 609-614.

Bigland-Ritchie, B., C. G. Kukulka, O. C. Lippold and J. J. Woods (1982). "The absence of neuromuscular transmission failure in sustained maximal voluntary contractions." J Physiol 330: 265-278.

Bo, K., M. Sherburn and T. Allen (2003). "Transabdominal ultrasound measurement of pelvic floor muscle activity when activated directly or via a transversus abdominis muscle contraction." Neurourology and Urodynamics 22(6): 582-588.

Boissonnault, J. S. and M. J. Blaschak (1988). "Incidence of diastasis recti abdominis during the childbearing year." Phys Ther 68(7): 1082-1086.

Boissonnault, J. S. and M. J. Blaschak (1988). "Incidence of Diastasis Recti Abdominis during the Childbearing Year." Physical Therapy 68(7): 1082-1086.

Borders, N. (2006). "After the Afterbirth: A Critical Review of Postpartum Health Relative to Method of Delivery." The Journal of Midwifery & Women□™s Health 51(4): 242-248.

Borg, G. A. (1982). "Psychophysical bases of perceived exertion." Med Sci Sports Exerc 14(5): 377-381.

Bost, B. (2000). "Should elective cesarean birth be offered at term as an alternative to labor and delivery for prevention of complications, including symptomatic pelvic prolapse, as well as stress urinary and fecal incontinence?" Obstetrics & Gynecology 95(4).

Brown, R. E., D. L. Edwards and J. M. Jakobi (2010). "Sex differences in force steadiness in three positions of the forearm." Eur J Appl Physiol 110(6): 1251-1257.

Brown, S. H. M. and S. M. McGill (2009). "Transmission of Muscularly Generated Force and Stiffness Between Layers of the Rat Abdominal Wall." Spine 34(2): E70-E75.

Buysse, D. J., C. F. Reynolds, T. H. Monk, S. R. Berman and D. J. Kupfer (1989). "The Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research." Psychiatry Res 28(2): 193-213.

Carter, S. L., C. Rennie and M. A. Tarnopolsky (2001). "Substrate utilization during endurance exercise in men and women after endurance training." Am J Physiol Endocrinol Metab 280(6): E898-907.

Chearskul, S. (2006). "Endocrine aspects of pregnancy." Siriraj Medical Journal 58(8): 977-979.

Cheng, C. Y., E. R. Fowles and L. O. Walker (2006). "Continuing education module: postpartum maternal health care in the United States: a critical review." J Perinat Educ 15(3): 34-42.

Christou, E. A., J. M. Jakobi, A. Critchlow, M. Fleshner and R. M. Enoka (2004). "The 1- to 2-Hz oscillations in muscle force are exacerbated by stress, especially in older adults." J Appl Physiol (1985) 97(1): 225-235.

Clark, B. C., S. R. Collier, T. M. Manini and L. L. Ploutz-Snyder (2005). "Sex differences in muscle fatigability and activation patterns of the human quadriceps femoris." Eur J Appl Physiol 94(1-2): 196-206.

Clark, B. C., T. M. Manini, D. J. Thé, N. A. Doldo and L. L. Ploutz-Snyder (2003). "Gender differences in skeletal muscle fatigability are related to contraction type and EMG spectral compression." J Appl Physiol (1985) 94(6): 2263-2272.

Coldron, Y., M. J. Stokes, D. J. Newham and K. Cook (2008). "Postpartum characteristics of rectus abdominis on ultrasound imaging." Manual therapy 13(2): 112-121.

Cook, S. B., J. A. Kanaley and L. L. Ploutz-Snyder (2014). "Neuromuscular function following muscular unloading and blood flow restricted exercise." Eur J Appl Physiol 114(7): 1357-1365.

Cort, J. A., J. P. Dickey and J. Potvin (2013). "Trunk muscle contributions to L4-5 joint rotational stiffness following sudden trunk lateral bend perturbations." Journal of Electromyography and Kinesiology 23: 1334-1342.

Corton, M. M., K. Leveno, S. Bloom, J. Hauth, D. Rouse and C. Spong (2009). Williams Obstetrics: 23rd Edition, McGraw-Hill Education.

Cox, J. L., J. M. Holden and R. Sagovsky (1987). "Detection of postnatal depression. Development of the 10-item Edinburgh Postnatal Depression Scale." Br J Psychiatry 150: 782-786.

Cram, J. R. (2011). Cram's Introduction to Surface Electromyography. Sudbury, Massachusetts, Jones and Bartlett.

Critchley, D. (2002). "Instructing pelvic floor contraction facilitates transversus abdominis thickness increase during low-abdominal hollowing." Physiother Res Int 7(2): 65-75.

Declercq, E., D. Cunningham, C. Johnson and C. Sakala (2008). "Mothers' Reports of Postpartum Pain Associated with Vaginal and Cesarean Deliveries: Results of a National Survey." Birth 35(1): 16-24.

Deering, R., J. Senefeld, T. Pashibin, D. A. Neumann and S. Hunter (2017). "Muscle Function and Fatigability of Trunk Flexors in Males and Females." Biology of Sex Differences 8.

Derchak, P. A., A. W. Sheel, B. J. Morgan and J. A. Dempsey (2002). "Effects of expiratory muscle work on muscle sympathetic nerve activity." J Appl Physiol (1985) 92(4): 1539-1552.

Diener, M. H., L. A. Golding and D. Diener (1995). "Validity and reliability of a one-minute half sit-up test of abdominal strength and endurance." Sports Medicin, Training and Rehabilitation 6: 105-119.

El Ouaaid, Z., A. Shirazi-Adl, A. Plamondon and C. Larivière (2013). "Trunk strength, muscle activity and spinal loads in maximum isometric flexion and extension exertions: a combined in vivo-computational study." J Biomech 46(13): 2228-2235.

Enoka, R. M., E. A. Christou, S. K. Hunter, K. W. Kornatz, J. G. Semmler, A. M. Taylor and B. L. Tracy (2003). "Mechanisms that contribute to differences in motor performance between young and old adults." J Electromyogr Kinesiol 13(1): 1-12.

Enoka, R. M. and J. Duchateau (2008). "Muscle fatigue: what, why and how it influences muscle function." J Physiol 586(1): 11-23.

Ericksson Crommert, M., M. M. Ekblom and A. Thorstensson (2011). "Activation of transverse abdominis varies with postural demand in standing." Gait & Posture` 33: 473-477.

Escamilla, R., E. Babb, R. DeWitt, P. Jew, P. Kelleher, T. Burnham, J. Busch, K. D'Ana, R. Mowbray and R. Imamura (2006). "Electromyographic Analysis of Traditional and Nontraditional Abdominal Exercises: Implications for Rehabilitation and Training." Physical Therapy 86(5).

Fairbank, J. C. (2014). "Oswestry disability index." J Neurosurg Spine 20(2): 239-241.
Fairbank, J. C., J. Couper, J. B. Davies and J. P. O'Brien (1980). "The Oswestry low back pain disability questionnaire." Physiotherapy 66(8): 271-273.

Fairbank, J. C. and P. B. Pynsent (2000). "The Oswestry Disability Index." Spine (Phila Pa 1976) 25(22): 2940-2952; discussion 2952.

Farina, D. and F. Negro (2015). "Common synaptic input to motor neurons, motor unit synchronization, and force control." Exerc Sport Sci Rev 43(1): 23-33.
Gandevia, S. C. (2001). "Spinal and supraspinal factors in human muscle fatigue." Physiol Rev 81(4): 1725-1789.

Gildea, J. E., J. A. Hides and P. W. Hodges (2013). "Size and symmetry of trunk muscles in ballet dancers with and without low back pain." J Orthop Sports Phys Ther 43(8): 525-533.

Gilleard, W. L. and J. M. M. Brown (1994). "An Electromyographic Validation of an Abdominal Muscle Test." Archives of Physical Medicine and Rehabilitation 75(9): 1002-1007.

Gilleard, W. L. and J. M. M. Brown (1996). "Structure and Function of the Abdominal Muscles in Primigravid Subjects During Pregnancy and the Immediate Postbirth Period." Journal of the American Physical Therapy Association 76(7): 750-762.

Gilleard, W. L., J. Crosbie and R. Smith (2002). "Static trunk posture in sitting and standing during pregnancy and early postpartum." Archives of Physical Medicine and Rehabilitation 83(12): 1739-1744.

Gilstrap III, L. C., F. G. Cunningham and J. P. Vandorsten (2002). Operative Obstetrics, McGraw-Hill Education/Medical.

Gollnick, P. D., P. Körge, J. Karpakka and B. Saltin (1991). "Elongation of skeletal muscle relaxation during exercise is linked to reduced calcium uptake by the sarcoplasmic reticulum in man." Acta Physiol Scand 142(1): 135-136.

Gracovetsky, S. (2008). "Is the lumbodorsal fascia necessary?" J Bodyw Mov Ther 12(3): 194-197.

Gracovetsky, S., H. Farfan and C. Lamy (1977). "A mathematical model of the lumbar spine using an optimized system to control muscles and ligamets." Orthop Clin North Am 8(1).

Graven-Nielsen, T. and L. Arendt-Nielsen (2002). "Peripheral and central sensitization in musculoskeletal pain disorders: an experimental approach." Curr Rheumatol Rep 4(4): 313-321.

Gutke, A., M. Lundberg, H. C. Ostgaard and B. Oberg (2011). "Impact of postpartum lumbopelvic pain on disability, pain intensity, health-related quality of life, activity level, kinesiophobia, and depressive symptoms." European Spine Journal 20(3): 440-448.

Gutke, A., H. Ostgaard and B. Oberg (2008). "Association between muscle function and low back pain in relation to pregnancy." Journal of Rehabilitation Medicine 40: 304-311.

Gutke, A., H. C. Ostgaard and B. Oberg (2008). "Association between muscle function and low back pain in relation to pregnancy." Journal of Rehabilitation Medicine 40(4): 304-311.

Häggmark, T. and A. Thorstensson (1979). "Fibre types in human abdominal muscles." Acta Physiol Scand 107(4): 319-325.

Hall, G. L., R. K. Hetzler, D. Perrin and A. Weltman (1992). "Relationship of timed sit-up tests to isokinetic abdominal strength." Res Q Exerc Sport 63(1): 80-84.

Hamilton, B. E., J. A. Martin, M. J. K. Osterman, S. C. Curtin and T. J. Mathews (2015). Births: Final Data for 2014. U. S. D. o. H. a. H. Services, C. f. D. C. a. Prevention, N. C. f. H. Statistics and N. V. S. System. 64.

Harmer, A. R., P. A. Ruell, S. K. Hunter, M. J. McKenna, J. M. Thom, D. J. Chisholm and J. R. Flack (2014). "Effects of type 1 diabetes, sprint training and sex on skeletal muscle sarcoplasmic reticulum Ca2+ uptake and Ca2+-ATPase activity." J Physiol 592(3): 523-535.

Haskell, W. L., I. M. Lee, R. R. Pate, K. E. Powell, S. N. Blair, B. A. Franklin, C. A. Macera, G. W. Heath, P. D. Thompson and A. Bauman (2007). "Physical activity and public health: updated recommendation for adults from the American College of Sports Medicine and the American Heart Association." Med Sci Sports Exerc 39(8): 1423-1434.

Hemingway, A. E., L. Herrington and A. L. Blower (2003). "Changes in muscle strength and pain in response to surgical repair of posterior abdominal wall disruption followed by rehabilitation." Br J Sports Med 37(1): 54-58.

Hides, J., W. Stanton, M. Freke, S. Wilson, S. McMahon and C. Richardson (2008). "MRI study of the size, symmetry and function of the trunk muscles among elite cricketers with and without low back pain." Br J Sports Med 42(10): 809-813.

Hides, J. A., C. L. Boughen, W. R. Stanton, M. W. Strudwick and S. J. Wilson (2010). "A magnetic resonance imaging investigation of the transversus abdominis muscle during drawing-in of the abdominal wall in elite Australian Football League players with and without low back pain." J Orthop Sports Phys Ther 40(1): 4-10.

Hides, J. A., I. Wong, S. J. Wilson, D. L. Belavy and C. A. Richardson (2007). "Assessment of abdominal muscle function during a simulated unilateral weight-bearing task using ultrasound imaging." Journal of Orthopaedic & Sports Physical Therapy 37(8): 467-471.

Hislop, H. J. and J. Montgomery (2002). Daniels and Worthingham's Muscle Testing: Techniques of Manual Examination. Philadelphia, Pennslyvania, Saunders.

Hodges, P. W., A. Kaigle Holm, S. Holm, L. Ekström, A. Cresswell, T. Hansson and A. Thorstensson (2003). "Intervertebral stiffness of the spine is increased by evoked

contraction of transversus abdominis and the diaphragm: in vivo porcine studies." Spine (Phila Pa 1976) 28(23): 2594-2601.

Hodges, P. W., A. Kaigle Holm, S. Holm, L. C. A. Ekstrom, T. Hansson and A. Thorstensson (2003). "Intervertebral Stiffness of the Spine is Increased by Evoked Contraction of Transversus Abdominis and the Diaphragm: In Vivo Porcine Studies." Spine 28(23): 2594-2601.

Hodges, P. W. and G. L. Moseley (2003). "Pain and motor control of the lumbopelvic region: effect and possible mechanisms." J Electromyogr Kinesiol 13(4): 361-370.

Hodges, P. W. and C. A. Richardson (1996). "Inefficient muscular stabilization of the lumbar spine associated with low back pain - A motor control evaluation of transversus abdominis." Spine 21(22): 2640-2650.

Hodges, P. W. and C. A. Richardson (1997). "Contraction of the abdominal muscles associated with movement of the lower limb." Physical Therapy 77(2): 132-142.

Hodges, P. W. and C. A. Richardson (1997). "Relationship between limb movement speed and associated contraction of the trunk muscles." Ergonomics 40(11): 1220-1230.

Hodges, P. W. and C. A. Richardson (1999). "Altered trunk muscle recruitment in people with low back pain with upper limb movement at different speeds." Archives of Physical Medicine and Rehabilitation 80(9): 1005-1012.

Hoeger Bement, M. K., J. Dicapo, R. Rasiarmos and S. K. Hunter (2008). "Dose response of isometric contractions on pain perception in healthy adults." Med Sci Sports Exerc 40(11): 1880-1889.

Hoeger Bement, M. K., A. Weyer, S. Hartley, B. Drewek, A. L. Harkins and S. K. Hunter (2011). "Pain perception after isometric exercise in women with fibromyalgia." Arch Phys Med Rehabil 92(1): 89-95.

Horton, T. J., M. J. Pagliassotti, K. Hobbs and J. O. Hill (1998). "Fuel metabolism in men and women during and after long-duration exercise." J Appl Physiol (1985) 85(5): 1823-1832.

Hungerford, B., W. Gilleard and P. W. Hodges (2003). "Evidence of Altered Lumbopelvic Muscle Recruitment in the Presence of Sacroiliac Joint Pain." Spine 28(14): 1593-1600.

Hunter, S. K. (2014). "Sex differences in human fatigability: mechanisms and insight to physiological responses." Acta Physiol (Oxf) 210(4): 768-789.

Hunter, S. K. (2016). "The Relevance of Sex Differences in Performance Fatigability." Med Sci Sports Exerc 48(11): 2247-2256.

Hunter, S. K. (2016). "Sex differences in fatigability of dynamic contractions." Exp Physiol 101(2): 250-255.

Hunter, S. K., J. E. Butler, G. Todd, S. C. Gandevia and J. L. Taylor (2006). "Supraspinal fatigue does not explain the sex difference in muscle fatigue of maximal contractions." J Appl Physiol (1985) 101(4): 1036-1044.

Hunter, S. K., A. Critchlow and R. M. Enoka (2004). "Influence of aging on sex differences in muscle fatigability." J Appl Physiol (1985) 97(5): 1723-1732.

Hunter, S. K., A. Critchlow, I. S. Shin and R. M. Enoka (2004). "Fatigability of the elbow flexor muscles for a sustained submaximal contraction is similar in men and women matched for strength." J Appl Physiol (1985) 96(1): 195-202.

Hunter, S. K., A. Critchlow, I. S. Shin and R. M. Enoka (2004). "Men are more fatigable than strength-matched women when performing intermittent submaximal contractions." J Appl Physiol (1985) 96(6): 2125-2132.

Hunter, S. K. and R. M. Enoka (2001). "Sex differences in the fatigability of arm muscles depends on absolute force during isometric contractions." J Appl Physiol (1985) 91(6): 2686-2694.

Hunter, S. K. and R. M. Enoka (2003). "Changes in muscle activation can prolong the endurance time of a submaximal isometric contraction in humans." J Appl Physiol (1985) 94(1): 108-118.

Hunter, S. K., H. M. Pereira and K. G. Keenan (2016). "The Aging Neuromuscular System and Motor Performance." J Appl Physiol (1985): jap.00475.02016.

Hunter, S. K., D. L. Ryan, J. D. Ortega and R. M. Enoka (2002). "Task differences with the same load torque alter the endurance time of submaximal fatiguing contractions in humans." J Neurophysiol 88(6): 3087-3096.

Hunter, S. K., J. M. Schletty, K. M. Schlachter, E. E. Griffith, A. J. Polichnowski and A. V. Ng (2006). "Active hyperemia and vascular conductance differ between men and women for an isometric fatiguing contraction." J Appl Physiol (1985) 101(1): 140-150.

Janssen, I., S. B. Heymsfield, Z. M. Wang and R. Ross (2000). "Skeletal muscle mass and distribution in 468 men and women aged 18-88 yr." J Appl Physiol (1985) 89(1): 81-88.

Jesunathadas, M., M. Klass, J. Duchateau and R. M. Enoka (2012). "Discharge properties of motor units during steady isometric contractions performed with the dorsiflexor muscles." J Appl Physiol (1985) 112(11): 1897-1905.

Johannes, C. B., T. K. Le, X. Zhou, J. A. Johnston and R. H. Dworkin (2010). "The prevalence of chronic pain in United States adults: results of an Internet-based survey." J Pain 11(11): 1230-1239.

Keller-Ross, M. L., H. M. Pereira, J. Pruse, T. Yoon, B. Schlinder-Delap, K. A. Nielson and S. K. Hunter (2014). "Stressor-induced increase in muscle fatigability of young men and women is predicted by strength but not voluntary activation." J Appl Physiol (1985) 116(7): 767-778.

Keller-Ross, M. L., B. Schlinder-Delap, R. Doyel, G. Larson and S. K. Hunter (2014). "Muscle fatigability and control of force in men with posttraumatic stress disorder." Med Sci Sports Exerc 46(7): 1302-1313.

Keller, M. L., J. Pruse, T. Yoon, B. Schlinder-Delap, A. Harkins and S. K. Hunter (2011). "Supraspinal fatigue is similar in men and women for a low-force fatiguing contraction." Med Sci Sports Exerc 43(10): 1873-1883.

Kendall, F. and E. McCreary (1983). Muscles: Testing and Function. Baltimore, MD, Williams & Wilkins.

Kendall, H., F. Kendall and D. Boynton (1952). Posture and Pain. Baltimore, MD, Williams & Wilkins.

Kim, P., L. Strathearn and J. E. Swain (2016). "The maternal brain and its plasticity in humans." Horm Behav 77: 113-123.

Kosek, E. and L. Lundberg (2003). "Segmental and plurisegmental modulation of pressure pain thresholds during static muscle contractions in healthy individuals." Eur J Pain 7(3): 251-258.

Kriska, A. M., W. C. Knowler, R. E. LaPorte, A. L. Drash, R. R. Wing, S. N. Blair, P. H. Bennett and L. H. Kuller (1990). "Development of questionnaire to examine relationship of physical activity and diabetes in Pima Indians." Diabetes Care 13(4): 401-411.

Kristiansson, P., K. Svardsudd and B. von Schoultz (1999). "Reproductive hormones and aminoterminal propeptide of type III procollagen in serum as early markers of pelvic pain during late pregnancy." American Journal of Obstetrics and Gynecology 180(1): 128-134.

Kulig, K., J. G. Andrews and J. G. Hay (1984). "Human Strength Curves." Exercise and Sport Sciences Reviews 12(1): 417-466.

Kumar, S. and Y. Narayan (1998). "Spectral parameters of trunk muscles during fatiguing isometric axial rotation in neutral posture." J Electromyogr Kinesiol 8(4): 257-267.

Lalatta Costerbosa, G., A. M. Barazzoni, M. L. Lucchi and R. Bortolami (1988). "Fiber Sizes and Histochemical Characteristics of the Rectus Abdominis Muscle of the Rabbit Under Conditions of Pregnancy and Mechanically Induced Stress." The Anatomical Record 222: 136-144.

Leavitt, M. (2008). 2008 Physical Activity Guidelines for Americans. U. S. D. o. H. a. H. Services.

Lee, D. G., L. J. Lee and L. McLaughlin (2008). "Stability, continence and breathing: The role of fascia following pregnancy and delivery." Journal of Bodywork and Movement Therapies 12: 333-348.

Lemley, K. J., B. Drewek, S. K. Hunter and M. K. Hoeger Bement (2014). "Pain relief after isometric exercise is not task-dependent in older men and women." Med Sci Sports Exerc 46(1): 185-191.

Lemley, K. J., J. Senefeld, S. K. Hunter and M. Hoeger Bement (2016). "Only women report increase in pain threshold following fatiguing contractions of the upper extremity." Eur J Appl Physiol 116(7): 1379-1385.

Liaw, L.-J., M.-J. Hsu, C.-F. Liao, M.-F. Liu and A.-T. Hsu (2011). "The Relationships Between Inter-recti Distance Measured by Ultrasound Imaging and Abdominal Muscle Function in Postpartum Women: A 6-Month Follow-up Study." Journal of Orthopaedic & Sports Physical Therapy 41(6): 435-443.

Liddle, S. D. and V. Pennick (2015). "Interventions for preventing and treating low-back and pelvic pain during pregnancy (Review) " Cochrane Database of Systematic Reviews(9): 1-116.

Liebenson, C., A. Karpowics, S. Brown, S. Howarth and S. McGill (2009). "The active straight leg raise test and lumbar spine stability." American Academy of Physical Medicine and Rehabilitation 1: 530-535.

Lobel, M. and R. S. DeLuca (2007). "Psychosocial sequelae of cesarean delivery: Review and analysis of their casues and implications." Social Science & Medicine 64: 2272-2284.

MacLennan, A., A. Taylor, D. Wilson and D. Wilson (2000). "The prevalance of pelvic floor disorders and their relationship to gender, age, parity and mode of delivery." British Journal of Obstetrics and Gynaecology 107: 1460-1470.

Manohar, M. (1986). "Blood flow to the respiratory and limb muscles and to abdominal organs during maximal exertion in ponies." J Physiol 377: 25-35.

Mast, B. A. (1999). "Alleviation of urinary incontinence after abdominoplasty." Ann Plast Surg 42(4): 456-457.

McQuade, K. J., J. A. Turner and D. M. Buchner (1988). "Physical Fitness and Chronic Low Back Pain." Clinical Orthopedics and Related Research 233: 198-204.

Melzack, R. (1987). "The short-form McGill Pain Questionnaire." Pain 30(2): 191-197.

Mens, J., A. Vleeming, C. Snijders, B. Koes and H. Stam (2002). "Validity of the active straight leg raise test for measuring disease severity in patients with posterior pelvic pain after pregnancy." Spine 27(2): 196-200.

Mens, J. M., A. Vleeming, C. J. Snijders, B. W. Koes and H. J. Stam (2001). "Reliability and validity of the active straight leg raise test in posterior pelvic pain since pregnancy." Spine (Phila Pa 1976) 26(10): 1167-1171.

Mens, J. M., A. Vleeming, C. J. Snijders, H. J. Stam and A. Z. Ginai (1999). "The active straight leg raising test and mobility of the pelvic joints." Eur Spine J 8(6): 468-473.

Mens, J. M. A., Y. H. H. in 't Veld and A. Pool-Goudzwaard (2012). "The Active Straight Leg Raise test in lumbopelvic pain during pregnancy." Manual therapy 17(4): 364-368.

Merskey, H., N. Bogduk and International Association for the Study of Pain. Task Force on Taxonomy. (1994). Classification of chronic pain : descriptions of chronic pain syndromes and definitions of pain terms. Seattle, IASP Press.

Merton, P. A. (1954). "Voluntary strength and fatigue." J Physiol 123(3): 553-564.

Mittendorfer, B., J. F. Horowitz and S. Klein (2002). "Effect of gender on lipid kinetics during endurance exercise of moderate intensity in untrained subjects." Am J Physiol Endocrinol Metab 283(1): E58-65.

Moffroid, M. T. (1997). "Endurance of trunk muscles in persons with chronic low back pain: assessment, performance, training." J Rehabil Res Dev 34(4): 440-447.

Naugle, K., R. Fillingim and J. Riley III (2012). "A Meta-Analytic Review of the Hypoalgestic Effects of Exercise." The Journal of Pain 13(12): 1139-1150.

Negishi, S., Y. Li, A. Usas, F. Fu and J. Huard (2005). "The Effect of Relaxin Treatment on Skeletal Muscle Injuries." The American Journal of Sports Medicine 33(12): 1816-1824.

Neumann, D. A. (2016). Kinesiology of the Musculoskeletal System: Foundations for Rehabilitation, Mosby Elsevier.

Neumann, P. and V. Gill (2002). "Pelvic floor and abdominal muscle interaction: EMG activity and intra-abdominal pressure." Int Urogynecol J Pelvic Floor Dysfunct 13(2): 125-132.

Ng, J. K., M. Parnianpour, C. A. Richardson and V. Kippers (2003). "Effect of fatigue on torque output and electromyographic measures of trunk muscles during isometric axial rotation." Arch Phys Med Rehabil 84(3): 374-381.

Nordin, M., N. Kahanovitz, R. Verderame, M. Parnianpour, S. Yabut, K. Viola, N. Greenidge and M. Mulvihill (1987). "Normal trunk muscle strength and endurance in women and the effect of exercises and electrical stimulation. Part 1: Normal endurance and trunk muscle strength in 101 women." Spine (Phila Pa 1976) 12(2): 105-111.

O'Sullivan, P. B., D. J. Beales, J. A. Beetham, J. Cripps, F. Graf, I. B. Lin, B. Tucker and A. Avery (2002). "Altered motor control strategies in subjects with sacroiliac joint pain during the active straight-leg-raise test." Spine (Phila Pa 1976) 27(1): E1-8.

Okubo, Y., K. Kaneoka, A. Imai, I. Shiina, M. Tatsumura, S. Izumi and S. Miyakawa (2010). "Electromyographic analysis of transversus abdominis and lumbar multifidus using wire electrodes during lumbar stabilization exercises." J Orthop Sports Phys Ther 40(11): 743-750.

Ostgaard, H. C., G. Zetherström and E. Roos-Hansson (1994). "The posterior pelvic pain provocation test in pregnant women." Eur Spine J 3(5): 258-260.

Parker, M. and A. Millar (2008). "Diastasis Rectus Abdominis and Lumbo-Pelvic Pain and Dysfunction-Are They Related?" Journal of Women's Health Physical Therapy 32(1): 15-22.

Parsons, C. L., J. Dell, E. J. Stanford, M. Bullen, B. S. Kahn, T. Waxell and J. A. Koziol (2002). "Increased prevalence of interstitial cystitis: previously unrecognized urologic and gynecologic cases identified using a new symptom questionnaire and intravesical potassium sensitivity." Urology 60(4): 573-578.

Phillips, K. and D. J. Clauw (2011). "Central pain mechanisms in chronic pain states--maybe it is all in their head." Best Pract Res Clin Rheumatol 25(2): 141-154.

Pool-Goudzwaard, A., G. H. van Dijke, M. van Gurp, P. Mulder, C. Snijders and R. Stoeckart (2004). "Contribution of pelvic floor muscles to stiffness of the pelvic ring." Clinical Biomechanics 19(6): 564-571.

Pool-Goudzwaard, A. L., M. C. Slieker ten Hove, M. E. Vierhout, P. H. Mulder, J. J. Pool, C. J. Snijders and R. Stoeckart (2005). "Relations between pregnancy-related low back pain, pelvic floor activity and pelvic floor dysfunction." Int Urogynecol J Pelvic Floor Dysfunct 16(6): 468-474.

Prather, H., S. Dugan, C. Fitzgerald and D. Hunt (2009). "Review of anatomy, evaluation, and treatment of musculoskeletal pelvic floor pain in women." PM R 1(4): 346-358.

Price, R. C., J. F. Asenjo, N. V. Christou, S. B. Backman and P. Schweinhardt (2013). "The role of excess subcutaneous fat in pain and sensory sensitivity in obesity." Eur J Pain 17(9): 1316-1326.

Racine, M., Y. Tousignant-Laflamme, L. A. Kloda, D. Dion, G. Dupuis and M. Choinière (2012). "A systematic literature review of 10 years of research on sex/gender and experimental pain perception - part 1: are there really differences between women and men?" Pain 153(3): 602-618.

Redfern, M., R. Hughes and D. Chaffin (1993). "High-pass filtering to remove electrocardiographic interference from torso EMG recordings." Clin Biomech (Bristol, Avon) 8(1): 44-48.

Richardson, C., G. Jull, P. Hodges and J. Hides (1999). "Therapeutic exercise for the spinal segmental stabilization in low back pain."

Richardson, C. A., C. J. Snijders, J. A. Hides, L. Damen, M. S. Pas and J. Storm (2002). "The relation between the transversus abdominis muscles, sacroiliac joint mechanics, and low back pain." Spine 27(4): 399-405.

Robinson, H., A. Mengshoel, M. Veierod and N. Vollestad (2010). "Pelvic girdle pain: Potential risk factors in pregnancy in relation to disability and pain intensity three months postpartum." Manual Therapy 15(6): 522-528.

Roepstorff, C., C. H. Steffensen, M. Madsen, B. Stallknecht, I. L. Kanstrup, E. A. Richter and B. Kiens (2002). "Gender differences in substrate utilization during submaximal exercise in endurance-trained subjects." Am J Physiol Endocrinol Metab 282(2): E435-447.

Roepstorff, C., M. Thiele, T. Hillig, H. Pilegaard, E. A. Richter, J. F. Wojtaszewski and B. Kiens (2006). "Higher skeletal muscle alpha2AMPK activation and lower energy charge and fat oxidation in men than in women during submaximal exercise." J Physiol 574(Pt 1): 125-138.

Ronchetti, I., A. Vleeming and J. P. van Wingerden (2008). "Physical characteristics of women with severe pelvic girdle pain after pregnancy: a descriptive cohort study." Spine (Phila Pa 1976) 33(5): E145-151.

Ross, R. M., J. N. Murthy, I. D. Wollak and A. S. Jackson (2010). "The six minute walk test accurately estimates mean peak oxygen uptake." BMC Pulm Med 10: 31.

Russ, D. W. and J. A. Kent-Braun (2003). "Sex differences in human skeletal muscle fatigue are eliminated under ischemic conditions." J Appl Physiol (1985) 94(6): 2414-2422.

Ryding, E. L., K. Wijma and B. Wijma (1998). "Predisposing psychological factors for posttraumatic stress reactions after emergency cesarean section." Acta Obstet Gynecol Scand 77(3): 351-352.

Sapsford, R. R. and P. W. Hodges (2001). "Contraction of the pelvic floor muscles during abdominal maneuvers." Arch Phys Med Rehabil 82(8): 1081-1088.

Sapsford, R. R., P. W. Hodges, C. A. Richardson, D. H. Cooper, S. J. Markwell and G. A. Jull (2001). "Co-activation of the abdominal and pelvic floor muscles during voluntary exercises." Neurourology and urodynamics 20(1): 31-42.

Sapsford, R. R., C. A. Richardson, C. F. Maher and P. W. Hodges (2008). "Pelvic floor muscle activity in different sitting postures in continent and incontinent women." Archives of Physical Medicine and Rehabilitation 89(9): 1741-1747.

Schiaffino, S. and C. Reggiani (2011). "Fiber types in mammalian skeletal muscles." Physiol Rev 91(4): 1447-1531.

Sjodahl, J., A. Gutke and B. Oberg (2013). "Predictors for long-term disability in women with persistent postpartum pelvic girdle pain." European Spine Journal 22(7): 1665-1673.

Smidt, G., T. Herring, L. Amundsen, M. Rogers, A. Russell and T. Lehmann (1983). "Assessment of abdominal and back extensor function. A quantitative approach and results for chronic low-back patients." Spine (Phila Pa 1976) 8(2): 211-219.

Smith, C. A., E. A. Smith, T. S. Parrott, B. H. Broecker and J. R. Woodard (1998). "Voiding function in patients with the prune-belly syndrome after Monfort abdominoplasty." J Urol 159(5): 1675-1679.

Söderquist, J., K. Wijma and B. Wijma (2002). "Traumatic stress after childbirth: the role of obstetric variables." J Psychosom Obstet Gynaecol 23(1): 31-39.

Sparling, P. B., M. Millard-Stafford and T. K. Snow (1997). "Development of a cadence curl-up test for college students." Res Q Exerc Sport 68(4): 309-316.

Spitznagle, T. M., F. C. Leong and L. R. Van Dillen (2007). "Prevalence of diastasis recti abdominis in a urogynecological patient population." International Urogynecology Journal 18(3): 321-328.

Stokes, I. A., M. G. Gardner-Morse and S. M. Henry (2011). "Abdominal muscle activation increases lumbar spinal stability: analysis of contributions of different muscle groups." Clin Biomech (Bristol, Avon) 26(8): 797-803.

Strasser, E. M., T. Draskovits, M. Praschak, M. Quittan and A. Graf (2013). "Association between ultrasound measurements of muscle thickness, pennation angle,

echogenicity and skeletal muscle strength in the elderly." Age (Dordr) 35(6): 2377-2388.

Stuge, B., A. Garratt, H. Krogstad Jenssen and M. Grotle (2011). "The pelvic girdle questionnaire: a condition-specific instrument for assessing activity limitations and symptoms in people with pelvic girdle pain." Phys Ther 91(7): 1096-1108.

Sullivan, M. J. L., S. R. Bishop and J. Pivik (1995). "The Pain Catastrophizing Scale: Development and validation." Psychological Assessment 7(4): 524-532.

Taylor, A. M., E. A. Christou and R. M. Enoka (2003). "Multiple features of motor-unit activity influence force fluctuations during isometric contractions." J Neurophysiol 90(2): 1350-1361.

Taylor, B. J., S. C. How and L. M. Romer (2006). "Exercise-induced abdominal muscle fatigue in healthy humans." Journal of Applied Physiology 100: 1554-1562.

Teyhen, D. S., N. W. Gill, J. L. Whittaker, S. M. Henry, J. A. Hides and P. Hodges (2007). "Rehabilitative ultrasound imaging of the abdominal muscles." J Orthop Sports Phys Ther 37(8): 450-466.

Thorstensson, A. and A. Arvidson (1982). "Trunk muscle strength and low back pain." Scand J Rehabil Med 14(2): 69-75.

Tracy, B. L. (2007). "Visuomotor contribution to force variability in the plantarflexor and dorsiflexor muscles." Hum Mov Sci 26(6): 796-807.

Tracy, B. L., D. V. Dinenno, B. Jorgensen and S. J. Welsh (2007). "Aging, visuomotor correction, and force fluctuations in large muscles." Med Sci Sports Exerc 39(3): 469-479.

Tracy, B. L., K. S. Maluf, J. L. Stephenson, S. K. Hunter and R. M. Enoka (2005). "Variability of motor unit discharge and force fluctuations across a range of muscle forces in older adults." Muscle Nerve 32(4): 533-540.

Urquhart, D. M., P. W. Hodges and I. H. Story (2005). "Postural activity of the abdominal muscles varies between regions of these muscles and between body positions." Gait Posture 22(4): 295-301.

Vaegter, H. B., G. Handberg and T. Graven-Nielsen (2014). "Similarities between exercise-induced hypoalgesia and conditioned pain modulation in humans." Pain 155(1): 158-167.

Vahratian, A. and T. R. Johnson (2009). "Maternity leave benefits in the United States: today's economic climate underlines deficiencies." Birth 36(3): 177-179.

Vera-Garcia, F., J. Moreside and S. McGill (2011). "Abominal muscle activation changes if the purpose is to control pelvis motion or thorax motion." Journal of Electromyography and Kinesiology 21(6): 893-903.

Vermani, E., R. Mittal and A. Weeks (2010). "Pelvic girdle pain and low back pain in pregnancy: a review." Pain Pract 10(1): 60-71.

Vleeming, A., H. B. Albert, H. C. Ostgaard, B. Sturesson and B. Stuge (2008). "European guidelines for the diagnosis and treatment of pelvic girdle pain." Eur Spine J 17(6): 794-819.

Vos, T., A. D. Flaxman, M. Naghavi, R. Lozano, C. Michaud, M. Ezzati, K. Shibuya, J. A. Salomon, S. Abdalla, V. Aboyans, J. Abraham, I. Ackerman, R. Aggarwal, S. Y. Ahn, M. K. Ali, M. Alvarado, H. R. Anderson, L. M. Anderson, K. G. Andrews, C. Atkinson, L. M. Baddour, A. N. Bahalim, S. Barker-Collo, L. H. Barrero, D. H. Bartels, M. G. Basáñez, A. Baxter, M. L. Bell, E. J. Benjamin, D. Bennett, E. Bernabé, K. Bhalla, B. Bhandari, B. Bikbov, A. Bin Abdulhak, G. Birbeck, J. A. Black, H. Blencowe, J. D. Blore, F. Blyth, I. Bolliger, A. Bonaventure, S. Boufous, R. Bourne, M. Boussinesq, T. Braithwaite, C. Brayne, L. Bridgett, S. Brooker, P. Brooks, T. S. Brugha, C. Bryan-Hancock, C. Bucello, R. Buchbinder, G. Buckle, C. M. Budke, M. Burch, P. Burney, R. Burstein, B. Calabria, B. Campbell, C. E. Canter, H. Carabin, J. Carapetis, L. Carmona, C. Cella, F. Charlson, H. Chen, A. T. Cheng, D. Chou, S. S. Chugh, L. E. Coffeng, S. D. Colan, S. Colquhoun, K. E. Colson, J. Condon, M. D. Connor, L. T. Cooper, M. Corriere, M. Cortinovis, K. C. de Vaccaro, W. Couser, B. C. Cowie, M. H. Criqui, M. Cross, K. C. Dabhadkar, M. Dahiya, N. Dahodwala, J. Damsere-Derry, G. Danaei, A. Davis, D. De Leo, L. Degenhardt, R. Dellavalle, A. Delossantos, J. Denenberg, S. Derrett, D. C. Des Jarlais, S. D. Dharmaratne, M. Dherani, C. Diaz-Torne, H. Dolk, E. R. Dorsey, T. Driscoll, H. Duber, B. Ebel, K. Edmond, A. Elbaz, S. E. Ali, H. Erskine, P. J. Erwin, P. Espindola, S. E. Ewoigbokhan, F. Farzadfar, V. Feigin, D. T. Felson, A. Ferrari, C. P. Ferri, E. M. Fèvre, M. M. Finucane, S. Flaxman, L. Flood, K. Foreman, M. H. Forouzanfar, F. G. Fowkes, R. Franklin, M. Fransen, M. K. Freeman, B. J. Gabbe, S. E. Gabriel, E. Gakidou, H. A. Ganatra, B. Garcia, F. Gaspari, R. F. Gillum, G. Gmel, R. Gosselin, R. Grainger, J. Groeger, F. Guillemin, D. Gunnell, R. Gupta, J. Haagsma, H. Hagan, Y. A. Halasa, W. Hall, D. Haring, J. M. Haro, J. E. Harrison, R. Havmoeller, R. J. Hay, H. Higashi, C. Hill, B. Hoen, H. Hoffman, P. J. Hotez, D. Hoy, J. J. Huang, S. E. Ibeanusi, K. H. Jacobsen, S. L. James, D. Jarvis, R. Jasrasaria, S. Jayaraman, N. Johns, J. B. Jonas, G. Karthikeyan, N. Kassebaum, N. Kawakami, A. Keren, J. P. Khoo, C. H. King, L. M. Knowlton, O. Kobusingye, A. Koranteng, R. Krishnamurthi, R. Lalloo, L. L. Laslett, T. Lathlean, J. L. Leasher, Y. Y. Lee, J. Leigh, S. S. Lim, E. Limb, J. K. Lin, M. Lipnick, S. E. Lipshultz, W. Liu, M. Loane, S. L. Ohno, R. Lyons, J. Ma, J. Mabweijano, M. F. MacIntyre, R. Malekzadeh, L. Mallinger, S. Manivannan, W. Marcenes, L. March, D. J. Margolis, G. B. Marks, R. Marks, A. Matsumori, R. Matzopoulos, B. M. Mayosi, J. H. McAnulty, M. M. McDermott, N. McGill, J. McGrath, M. E. Medina-Mora, M. Meltzer, G. A. Mensah, T. R. Merriman, A. C.

Meyer, V. Miglioli, M. Miller, T. R. Miller, P. B. Mitchell, A. O. Mocumbi, T. E. Moffitt, A. A. Mokdad, L. Monasta, M. Montico, M. Moradi-Lakeh, A. Moran, L. Morawska, R. Mori, M. E. Murdoch, M. K. Mwaniki, K. Naidoo, M. N. Nair, L. Naldi, K. M. Narayan, P. K. Nelson, R. G. Nelson, M. C. Nevitt, C. R. Newton, S. Nolte, P. Norman, R. Norman, M. O'Donnell, S. O'Hanlon, C. Olives, S. B. Omer, K. Ortblad, R. Osborne, D. Ozgediz, A. Page, B. Pahari, J. D. Pandian, A. P. Rivero, S. B. Patten, N. Pearce, R. P. Padilla, F. Perez-Ruiz, N. Perico, K. Pesudovs, D. Phillips, M. R. Phillips, K. Pierce, S. Pion, G. V. Polanczyk, S. Polinder, C. A. Pope, S. Popova, E. Porrini, F. Pourmalek, M. Prince, R. L. Pullan, K. D. Ramaiah, D. Ranganathan, H. Razavi, M. Regan, J. T. Rehm, D. B. Rein, G. Remuzzi, K. Richardson, F. P. Rivara, T. Roberts, C. Robinson, F. R. De Leòn, L. Ronfani, R. Room, L. C. Rosenfeld, L. Rushton, R. L. Sacco, S. Saha, U. Sampson, L. Sanchez-Riera, E. Sanman, D. C. Schwebel, J. G. Scott, M. Segui-Gomez, S. Shahraz, D. S. Shepard, H. Shin, R. Shivakoti, D. Singh, G. M. Singh, J. A. Singh, J. Singleton, D. A. Sleet, K. Sliwa, E. Smith, J. L. Smith, N. J. Stapelberg, A. Steer, T. Steiner, W. A. Stolk, L. J. Stovner, C. Sudfeld, S. Syed, G. Tamburlini, M. Tavakkoli, H. R. Taylor, J. A. Taylor, W. J. Taylor, B. Thomas, W. M. Thomson, G. D. Thurston, I. M. Tleyjeh, M. Tonelli, J. A. Towbin, T. Truelsen, M. K. Tsilimbaris, C. Ubeda, E. A. Undurraga, M. J. van der Werf, J. van Os, M. S. Vavilala, N. Venketasubramanian, M. Wang, W. Wang, K. Watt, D. J. Weatherall, M. A. Weinstock, R. Weintraub, M. G. Weisskopf, M. M. Weissman, R. A. White, H. Whiteford, S. T. Wiersma, J. D. Wilkinson, H. C. Williams, S. R. Williams, E. Witt, F. Wolfe, A. D. Woolf, S. Wulf, P. H. Yeh, A. K. Zaidi, Z. J. Zheng, D. Zonies, A. D. Lopez, C. J. Murray, M. A. AlMazroa and Z. A. Memish (2012). "Years lived with disability (YLDs) for 1160 sequelae of 289 diseases and injuries 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010." Lancet 380(9859): 2163-2196.

Waddell, G., M. Newton, I. Henderson, D. Somerville and C. J. Main (1993). "A Fear-Avoidance Beliefs Questionnaire (FABQ) and the role of fear-avoidance beliefs in chronic low back pain and disability." Pain 52(2): 157-168.

Wang, X.-Q., J.-J. Zheng, Z.-W. Yu, X. Bi, S.-J. Lou, J. Liu, B. Ci, Y.-H. Hua, M. Wu, M.-L. Wei, H.-M. Shen, Y. Chen, Y.-J. Pan, G.-H. Xu and P.-J. Chen (2012). "A Meta-Analysis of Core Stability Exercise versus General Exercise for Chronic Low Back Pain." PLOS ONE 7(12).

Welsh, S. J., D. V. Dinenno and B. L. Tracy (2007). "Variability of quadriceps femoris motor neuron discharge and muscle force in human aging." Exp Brain Res 179(2): 219-233.

Whittaker, J. L., M. B. Warner and M. Stokes (2013). "Comparison of the sonographic features of the abdominal wall muscles and connective tissues in individuals with and without lumbopelvic pain." J Orthop Sports Phys Ther 43(1): 11-19.

Widgerow, A. D. (1992). "Abdominoplasty following colostomy." Ann Plast Surg 29(5): 454-456.

Woolf, C. J. (2011). "Central sensitization: implications for the diagnosis and treatment of pain." Pain 152(3 Suppl): S2-15.

Wu, W. H., O. G. Meijer, K. Uegaki, J. M. Mens, J. H. van Dieën, P. I. Wuisman and H. C. Ostgaard (2004). "Pregnancy-related pelvic girdle pain (PPP), I: Terminology, clinical presentation, and prevalence." Eur Spine J 13(7): 575-589.

Wust, R., C. Morse, A. de Haan, D. Jones and H. Degens (2008). "Sex differences in contractile properties and fatigue resistance of human skeletal muscle." Experimental Physiology 93: 843-850.