# TIME VARYING MOTION AND MUSCLE ACTIVATION PATTERNS DURING EXTREME CONDITIONING PROTOCOLS

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## Abstract

The popularity of Extreme Conditioning Protocols has increased in recent years. However, due to the high intensity and competitiveness, participants are at greater risk of injury. This thesis aims to quantify changes in muscle activation, kinematics, and discomfort of the squat and deadlift exercises during an Extreme Conditioning Protocol.

Twenty participants (minimum of 1 year experience, frequency of 2X/week) performed 5 sets of 8 deadlifts (60% 1RM), 8 front squats (60% 1RM), and 10 shoulder presses (35/25 lbs.). Average whole body kinematics, muscle activation, and discomfort ratings were measured. Significant changes were observed from the 1st round to 5th round in the trunk, hip and knee angles, muscle activation, and discomfort.

Despite using experienced individuals as participants, this research showed their movement patterns were affected by an extreme conditioning protocol performed with minimal rest. Therefore, participants should be conscious of their technique during this type of workout to prevent injury.

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## Glossary

| | |
|---|---|
| ACSM | American College of Sports Medicine |
| ANOVA | Analysis of variance |
| C7 | 7th cervical vertebrae |
| BF | Biceps femoris muscle |
| ECP | Extreme conditioning protocols |
| EMG | Electromyography |
| EO | External oblique muscle |
| ES | Erector spinae muscle |
| FMS | Functional Movement Screen |
| GM | Gluteus medius muscle |
| GT | Greater trochanter |
| IC | Iliac crest |
| IO | Internal oblique muscle |
| IRED | Infrared emitting diodes |
| L4 | 4th lumbar vertebrae |
| L5 | 5th lumbar vertebrae |
| LBP | Low back pain |
| LES | Lumbar erector spinae muscle |
| LT | Lower thoracic (spinal segment from $T_6$ to $T_{12}$) |
| MaxFlex | Maximum flexion |
| MVC | Maximum voluntary contraction |
| NIOSH | National Institute for Occupational Safety and Health |
| NSCA | National Strength and Conditioning Association |
| RA | Rectus abdominis muscle |

| | |
|---|---|
| Reps | Repetitions |
| RF | Rectus femoris muscle |
| ROM | Range of motion |
| RM | Repetition maximum |
| S1 | 1st sacral vertebrae |
| S2 | 2nd sacral vertebrae |
| T6 | 6th thoracic vertebrae |
| T12 | 12th thoracic vertebrae |
| TES | Thoracic erector spinae muscle |
| UT | Upper thoracic (spinal segment from $C_7$ to $T_6$) |
| VAS | Visual analog scale |

## **Conflict of Interest Statement**

The contributors to this MSc thesis are Stephen DiMonte (student) and Dr. Janessa D.M. Drake (supervisor). This statement certifies that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this thesis.

## 1. General Introduction

Benefits of resistance training have been established, ranging from increases in strength, muscle mass, power, endurance and bone density as well as decreases in fat mass (Hunter et al., 2014; Hurley & Roth, 2000). Recommended resistance training protocols are extremely diverse and are often tailored to meet the health profile as well as the unique goals of the individual. One type of resistance exercise, such as extreme conditioning protocols (ECP), have grown immensely in popularity in the past few years. ECPs, defined by the American College of Sports Medicine (ACSM), consist of high repetitions (reps), vigorous intensity workouts that involve challenging workouts performed in a specific order with short rest periods between sets. ECP workouts share many similarities with circuit training, but a main difference is a lack of resistance training machines and the addition of a timed or scored component. These conditioning workouts often involve a variety of resistance training methods involving barbells and kettlebells, explosive movements, repeated body mass exercises, sprints and flexibility. Strength and flexibility training improve performance and prevent injury. Flexibility of a joint is defined by joint architecture, and by joint capsule laxity, muscle, tendon, and ligament (Krivickas et al., 1996). Limited flexibility can alter the normal biomechanics of movement and produce early muscle fatigue (Krivickas et al., 1996). Strength training has shown improvements in maximal oxygen consumption and body composition have been observed (Smith et al., 2013) as well as self-reported increases in enjoyment and adherence rates (Heinrich et al., 2014). A study by Heinrich et al. (2014) randomized pre-test and post-test interventions by placing physically inactive, overweight participants (BMI > 30.5) into two groups: traditional aerobic exercise or ECP. The traditional aerobic exercise group completed workouts at a moderate intensity (60% max HR) for 50 minutes at a constant intensity, while the ECP group completed a

5-30 minute workout with varying intensity. The results from this study revealed that the ECP group displayed higher enjoyment levels and were more likely to continue based on post-test questionnaire results (Heinrich et al., 2014). While ECP have been and continue to be utilized in many different areas of fitness and performance, CrossFit™ may be credited with bringing this style of training protocol to the attention of the general exercising population. Despite several positive findings, exercise, fitness and strength conditioning professionals express concerns over the lack of agreement between ECP and current accepted training guidelines. Specifically, that performing intense high volume workouts combined with weights and multi-joint exercises requiring precise technique within a time limit may lead to unsafe movement execution and injury (Bergeron et al., 2011). Furthermore, anecdotal evidence from many exercise, fitness and strength conditioning professionals suggests that because participants are encouraged to complete the ECP workout as quickly as possible and are not instructed when they should rest (rest is self-selected by participants), poor technique is inevitable which may increase the chances of injury. Despite this belief, there is no evidence of increased injury rates for ECP relative to other common recreational and competitive activities such as weightlifting, running, and fitness club activities. Injury rates with CrossFit™ training are similar to that reported in the literature for sports such as Olympic weight-lifting, power-lifting and gymnastics and lower than competitive contact sports such as rugby union and rugby league (Hak et al., 2013). A unique aspect of ECP is that participants are able to control the duration and frequency of their rest periods while being encouraged to complete the workout as quickly as possible with proper technique. Moreover, ECP typically involve a competitive component where participants are trying to achieve a better score or time than their peers. The optional rest periods combined with the competitive nature of ECP may lead to participants taking inadequate rest throughout the workout. Since heart rate has been shown to be an accurate predictor of exercise intensity (Strath et al. 2000), an increasing heart rate during an ECP would be suggest participants are not taking adequate rest. As a result of how recent ECP have come to prominence in the general population, there are relatively few studies examining its short and long-term effects. Recreational weight lifting has been documented to have short and long term effects on low back pain (LBP) (Hagen et al., 1994). Hooper et al. (2014) examined technique changes during the squat exercise during ECP and found that as participants progressed through the workout, hip and knee angles varied. However, no studies to date have demonstrated a link between ECP and an increased risk of LBP. Therefore, the purpose of this study was to investigate the changes in kinematics, muscle activation, and discomfort of the trunk while performing the deadlift exercise (deadlift) and squat exercises (squat) during an ECP.

### *1.1 Research Aims*

The aims of this thesis were:

1. To quantify the motion and muscle activation characteristics of the thoracic and lumbar spine during ECP.
2. To determine if motion and muscle activation characteristics are consistent between rounds during ECP.
3. To determine if participants experience in ECP maintain their form and intensity throughout the workout (indicating they can use an adequate amount of self-selected rest).
4. To determine if ECP cause discomfort on the thoracic and lumbar spine.

### *1.2 Hypotheses*

In this thesis, we define a round based on CrossFit™ standards. A round is defined by completing a series of exercises with a set number of reps with proper form.

1. There would be significant changes in kinematic measures of trunk and knee angles in both the deadlift and squat exercises across the 1st to the 5th rounds.
2. Activation of the hip and trunk musculature will increase significantly during both the squat and deadlift exercises across the 1st to the 5th rounds.
3. Heart rate would increase in response to the number of rounds completed. Heart rate will be positively associated with time.
4. Experienced ECP participants would not report clinically significant discomfort scores (<10mm on a 100mm Visual Analog Scale VAS) during the workout.

# 2. Literature Review

## *2.1 Anatomy of the Spine*

Understanding the anatomy of the spine and its components is beneficial when discussing kinematics, muscle activation and injuries. The spine is made up of seven cervical vertebrae, 12 thoracic vertebrae, five lumbar vertebrae, and five fused sacral vertebrae (White & Panjabi, 1990). The shape of the vertebrae, in particular the articulating superior and inferior facets, help to guide and limit motion in the spine (Panjabi and White, 1980). The smallest motion segment of the spine is the functional spine unit (FSU), which consists of two vertebrae, intervertebral discs (IVD) and end plates (Figure 2.1) (Nordin et al., 2001). The IVD, ligaments and muscles work synergistically to allow the spine to flex and extend, twist along its axis, and bend laterally (Ebraheim et al., 2004). The IVD is comprised of three main components: the nucleus pulposus, the annulus fibrosus, and the cartilaginous end-plates. The nucleus pulposus, composed of translucent network of fibrous strands, is at the center of the spine surrounded at the top and bottom by the endplates. The annulus fibrosus, composed of collagenous fibers, encircles the nucleus pulposus and forms the outer boundary of the disc (White & Panjabi, 1990). Lastly, the cartilaginous end plate, composed on hyaline cartilage, transfers nutrients from the vertebral body to the IVD and acts as a barrier between the nucleus pulposus and annulus fibrosus from the vertebral body (Ebraheim et al., 2004).

Again, the ligaments and muscles work together to provide stability and motion of the spine (White & Panjabi, 1990). The anterior longitudinal ligament and the posterior longitudinal ligament are essential in movement and stabilization of the spine (Ebraheim et al., 2004). The chief extensors of the spine are the erector spinae muscles, which are typically divided into three longitudinal columns based on the section’s origin: iliocostalis, longissismus, and spinalis

(Tortora, 2005). Anatomy texts describe the spinalis, longissimus and iliocostalis muscles structurally (by slight variation of origins and insertions), but functionally it is more helpful to group these muscles together as one (erector spinae muscles; ES) and separate by region (pars thoracis, pars lumborum). The muscles are similar within a region, but the regions are different. The thoracic erector spinae (TES) contain 75% slow twitch muscle, while the lumbar erector spinae (LES) contain 50% slow twitch and 50% fast twitch muscle (McGill, 2016). The TES tendons have a large moment arm and a line of action that is parallel to the compressive axis, whereas the LES has a relatively shorter moment arm with a line of action perpendicular to the compressive axis (McGill, 2016). This means the TES can create greater extension moment with less force and so lower compressive penalty due to the larger moment arm. Conversely the LES, when the spine is in a near neutral position, can also act to produce an extension moment but importantly can resist anterior shear of the trunk. These anterior shear forces are those that are present as the upper body flexes, such as during lifting, causing the superior vertebrae to slide anteriorly with respect to the inferior vertebrae. If left unchecked, this anterior shear will damage the spinal cord and nerves. When the lumbar spine flexes (becomes non-neutral) the LES line of action reorients to become parallel with the spine and can no longer produce posterior shear (can only generate extension moment and compressive force) (McGill, 2016). When the LES muscles lose their ability to resist anterior shear force, that are present during all forward flexion of the trunk (i.e. during lifting), this loading shifts to the passive elements of the FSU. These passive elements, that include the IVD and ligaments described above, are not optimally designed to resist repetitive and/or sustained anterior shear, and so become damaged with this type of loading. This is why neutral spine postures are important to reduce the risk of a low back injury when performing repetitive or heavy lifting (McGill, 2016). Flexion has been the primary focus of most spine research. During flexion (forward bending), the weight of the trunk causes the erector spinae muscles to increase in activity (White & Panjabi, 1990). Once at end range of motion (ROM), the muscle activity ceases, leaving the ligaments and other passive tissues to resist the forward bending moment (McGill, 2002).

The spine and the intervertebral disc are exposed to injury from external force(s) or movement of the spine through combined flexion, lateral bending, and twisting (Pope et al., 1991; White & Panjabi, 1990). This lead the National Institute for Occupational Safety and Health (NIOSH) to propose a weight limit to safely complete a lifting task without an increased risk of developing LBP (Waters et al., 1993). The NIOSH weight restriction is 3400 N of compression and going beyond this limit can result in a lifting-related low back injury. Repetitive lifting and loading of the spine is known to cause injury however generating a model to predict cumulative loading limits has been elusive (Fischer et al., 2007). McGill et al. (1998) recommends a maximum acceptable lumbar shear force of 1000N for single exposures. However, the maximum tolerable load changes depending on the position of the spine. More specifically, as an individual bends forward and the spine becomes flexed, the line of action of the extensor muscles changes and therefore decreases the amount of shear force they can support (McGill et al., 2000). Shear force causes adjacent vertebrae to slide in opposite directions perpendicular to the length of the spine. Previous research has linked shear force as a risk factor to low back injury (Yingling & McGill, 1999) at much lower levels than compression (i.e. 500 N vs 3400N respectively; McGill 2016). A common mechanism of injury is the combination of non-neutral flexion/extension postures in relation to normal upright standing with axial twist (Drake and Callaghan, 2008). According to Peach et al. (1998) the typical ROM in the lumbar spine is 71° of flexion/extension, 30° for lateral bend, and 17° for axial twist.

### *2.2 Low Back Pain and Exercise*

LBP is responsible for the increasing health care costs in North America (Nelson-Wong et al., 2008) and considered to be one of the most costly disabilities worldwide (Lis et al., 2007). In Ontario in 2014, LBP made up the largest number of disability claims and had a direct cost of $475 million and an indirect cost of $1.4 billion due to lost wages, lower productivity, retraining etc. (Hoy et al. 2014). LBP accounts for a significant portion of work place injuries and between 60-85% of the population will experience LBP at one point in their lives (Bird and Payne, 1999). Many treatment options are available to help treat, cure and manage LBP such as acupuncture, physiotherapy, sports therapy, prescription and over the counter drugs, injections, and in severe cases surgery. Exercise programs are the most widely used conservative strategy for treatment and prevention of LBP. Specifically, resistance training has been shown to reduce injury risk of LBP (Steele et al., 2015). However, variables such as volume (total number of reps in a workout), frequency, load, speed, reps (reps) affect overall effort contributed during a resistance training program (Steele et al., 2015). Previous research has suggested an optimal range of loading and stress applied to the spine that promotes disc regeneration and overall health of the FSU. Steele et al., (2015) suggested a resistance training program using high loads, low volume and low frequency be most beneficial for spine health. In summary, while lifting can be a major cause of LBP it can also strengthen the back and spine to better tolerate future loads and become more resilient if done properly.

### *2.3 Technique, Fatigue, and Proprioception*

Many different models have been proposed to explain the process by which fatigue occurs. The cardiovascular model states that fatigue occurs as a result of cardiac output not meeting the demands of the muscles. The muscle recruitment model states that with repetitive activation of a muscle, the neural recruitment abilities of the central nervous system are decreased resulting in decreased contractile force of the muscle. The biomechanical model of fatigue states that fatigue is identified by a loss of elastic energy return and a delay in the stretch shortening cycle of a muscle (Noakes, 2000). The relationship between motor control and technique are well documented in literature regarding repetitive lifting that causes fatigue. Johnston et al. (1988) observed significant decreases in motor control by measuring healthy university aged participants' ability to balance after performing a fatiguing protocol. Balance was measured by the length of time participants were able to balance on an unstable board used for fitness applications. The authors suggested that fatigue interfered with some element of the proprioceptive feedback loop, possibly muscle spindle desensitization (Johnston et al., 1988). Lattanzio et al. (1997) evaluated heavy exercise bouts and determined that individuals' ability to reproduce certain knee angles is diminished, which may lead to altered motion and joint stability. This study required healthy, university aged participants to undergo an exhausting bout on a cycle ergometer until exhaustion. Immediately after this bout, participants were asked to perform a two legged squat and produce a target knee angle (Johnston et al., 1988). In addition to the loss of motor control, proper technique is also affected. Hooper et al. (2014), examined the effect of ECP and fatigue on the mechanics of the squat. Healthy, university aged participants who were experienced with weightlifting but not ECP were instructed to complete a popular ECP workout (Hooper et al., 2014) As expected, as participants became progressed through the workout, technique was altered and more variable (Hooper et al., 2014). When examining the squat, these authors noted that both men and women adopted a squat with an increase forward lean and less knee flexion. Hooper et al. (2014) suggest that proprioception may not be the only factor leading to technique changes when fatigued, as the indicators of fatigues showed very low correlation with altered kinematics. These studies demonstrate how movement patterns may change with certain parameters of a task.

LBP has been linked with reduced coordination between the trunk and pelvis segments (Seay and Hamill, 2011). Specifically, Seay and Hamill (2011) examined the variability of coordination between the trunk and pelvis segments in individuals with LBP. Their results show that during running and walking tasks individuals with LBP exhibit reduced coordination between the trunk and pelvis segments compared to non-symptomatic individuals. Furthermore, a lumbar extensor muscle fatiguing protocol can alter the postural angles between the lumbar and pelvis. Hu & Ning (2014) examined the relationship between lumbo-pelvic coordination patterns and lumbar muscle fatigue. These authors concluded that changes in hip and spine angles due to fatigue could elevate the L5/S1 joint loading and in turn increase risk of LBP (Hu & Ning, 2014). The association of lumbo-pelvic control and LBP was also investigated by Nelson-Wong et al. (2013), that used a test designed to measure an individual's lumbo-pelvic control and compare the test scores between groups with LBP to those without LBP. These authors discovered that individuals suffering from LBP had less lumbo-pelvic control than those without LBP. Nelson-Wong et al. (2013) note that it is not clear whether lumbo-pelvic is the cause of LBP or an associated symptom. The latter two studies differed in that Nelson-Wong(2013) studied individuals with pre-existing weakness while Hu and Ning(2014) created a weakness through fatigue. Regardless, these studies suggest that a lack of lumbo-pelvic control makes individuals susceptible to LBP.

The effect of muscle fatigue on coordination has also been studied in manual handling scenarios. A review of literature on lifting techniques used in manual materials lifting was completed by Straker et al. (2003). In this review, Straker et al. (2003) describes three main lifting techniques commonly referred to; squat lift, stoop lift and semi squat lift. The squat lift was described as a lift with knee angles around 45° and a trunk angle around 30°. A stoop lift was defined as lift with knee angles of 135° and a trunk angle of 90°. The semi squat lift was defined as a lift with knee and torso angles midway between those that define the squat and stoop lifts. The major finding of the Straker et al. (2003) study is that while the squat lift is generally recommended, there is a lack of research that either lift is superior in terms of kinetics. McGill (2016) summarizes many years of research that provide evidence that the optimal lifting technique for manual materials handling depends on many things, including the size, shape, and weight of the object lifted, as well as the frequency at which the lifting must be performed (i.e. lifts/min in manufacturing). McGill (2016) further details that the key component to reducing the risk of a low back injury during lifting, regardless of technique used, is maintaining the lumbar spine in a near-neutral position (i.e. form during lift).

In a study that examined changes in timing of trunk muscle activation, general fatigue was compared to specific fatigue of low back extensor muscles (Gorelick et al., 2003). To elicit general fatigue a rowing workout was used while a prolonged isometric back extension was used to cause specific fatigue in the erector spinae muscle. Significantly higher changes in muscle activation during a manual lifting task after back extensor fatiguing protocol was reported when compared to a central fatiguing protocol. Gorelick et al. (2003) concluded that injury risk may be elevated during a lifting task despite the individuals not being aware of their own fatigue level. Moreover, these authors concluded that individuals need to be aware of not only the weight lifted and frequency of the lift but the length of time needed for the lift to take place (Gorelick et al., 2003). Another study investigating the different factors that affect lifting technique is an investigation of the Functional Movement Screen™ (FMS). Frost et al. (2013) investigated the influence of speed and load on an individual’s movement patterns. Movement screens under low load and speed were not predictive of how participants performed once both variables were increased. In typical resistance training, the load is clearly defined but in comparison with ECP, participants are permitted to select their own pace. Therefore, it is necessary to investigate how this affects an individual’s ability to safely and properly complete an ECP.

### *2.4 Current Training Guidelines*

According to the ACSM the basic structure of a traditional resistance training routine is broken down into load, sets and reps. Typically, a participant is to perform a certain amount of reps in a row without stopping (also known as a set). Participants will then rest for a predetermined amount of time between sets and this process is repeated until the prescribed amount of sets is completed (i.e. 3 sets of 8 reps each with 2-3 minutes of rest between sets). ACSM breaks down resistance training into four categories: muscular strength, muscular hypertrophy, muscular power, and muscular endurance. Muscular strength uses the heaviest loads, typically 80-100% of what the participant can successfully lift once. The heaviest weight a participant can lift only once is also known as their 1 rep maximum (1RM). Muscular endurance applies to the opposite end of the spectrum and utilizes lighter loads (<70% 1RM), higher reps (10-25), and less rest between each set (30-60 seconds (s)). Muscular power focuses on completing the reps as quick as possible using light weight similar but with fewer reps and longer rest periods. Lastly, hypertrophy, focuses on increasing muscular size through 70-85% 1RM, 3-6 sets, 1-12 reps per set, and 2-3 minutes (min) rest between sets. Current resistance training guidelines are variable, depending on the goal of the participant. As briefly described above, conventional resistance training guidelines requires a mandatory rest period between sets, whereas ECP direct participants to complete as many reps as possible in a set amount of time or complete a set number of reps as quickly as possible.  Therefore, the duration and frequency of rest intervals is left to the discretion of the participant, which is likely the main source of contention for this type of program. Regardless of training style, maintaining proper technique is an important factor to minimize injury risk. Rest allows participants to recover from the previous exertion and maintain proper technique throughout a workout. It is important to note that in ECP if a repetition is not performed with proper technique it is not considered complete. Whereas, in conventional resistance training, typically the participant is given assistance by a spotter to complete the required number of reps. It is currently unknown how fatigue influences a person's ability to discern when they require rest, therefore an investigation of this along with quantified biomechanics would be worthwhile.

### *2.5 ECP Studies*

ECP have been a popular workout style for military members to improve job specific fitness (Grier et al., 2013) for decades. ECP are a type of workout that targets large muscle groups using moderate to heavy loads. Typically several exercises along with a number of reps for each exercise will be prescribed (i.e. 10 pushups, 5 sit ups, 5 pull ups). Completing those three exercises makes up 1 round and ECP workouts may consist of any number of rounds. A round may also be referred to as a circuit, but for the purposes of this thesis the term "round" will be used. ECP involve a time component where the participant tries to complete the prescribed number of rounds as quickly as possible or complete as many rounds as possible in a set amount of time. In a review of ECP, Bergeron et al. (2011) expressed concern over the structure of this program due to the fact that these exercises are performed under a time constraint with insufficient rest intervals. Performing exercises as fast as possible without structured rest periods can result in poor movement execution and an increased risk of injury. Bergeron et al. (2011) stated this would lead to unsafe movement execution that oppose safe training guidelines and potentially lead to injury. In addition to this, the ACSM's recommends no less than 30s of rest should be taken between each set when resistance training (ACSM, 2015). The absence of a defined rest interval during ECP is a cause for concern since fatigue leads to reduced proprioception (Hooper et al., 2014), and the concern is this will lead to unsafe movement execution. However, Grier et al. (2013) found that injury rates for soldiers participating in ECP were no higher than those not participating over a 6-month period. In an 8-week exercise intervention taking place at a CrossFit™ gym, participants taking part in an ECP showed significant increases in oxygen consumption as well as decreases in body fat percentage (Smith et al., 2013). Furthermore, adolescents (age= 15.4 years, 51.5% female, 48.5% male) partaking in ECP workouts were more successful at improving select physical and body composition measures compared to various traditional sports of the adolescents' choice, such as ice skating, tennis, soccer etc. (Eather et al., 2015). These measures include waist circumference, BMI, sit and reach (flexibility), standing jump (power), shuttle run (cardiorespiratory fitness). An online questionnaire distributed through CrossFit™ forums that detailed the frequency and type of ECP injuries documented revealed that 73.5% of respondents had incurred an injury during ECP (Hak et al., 2013). These rates are analogous to injury rates during weightlifting, powerlifting, and gymnastics as well as recreational adult fitness activities (training at a fitness club and/or distance running) (Hak et al., 2013). While studies have not shown a disproportionately higher injury rate in ECP relative to other common fitness activities, the potential for an increased in injury rate are still a concern due to the rapidly growing popularity of ECP (becoming mainstream).

### *2.6 Literature Review Summary*

With the increase in popularity of ECP, it is necessary to examine its safety and efficacy. Previous studies evaluating the effects of fatigue have shown changes in movement patterns and a decrease in balance and proprioception. While alterations in movement patterns across rounds of an ECP have been shown in novices (Hooper et al., 2014), it is unknown whether these changes persist when participants become experienced.  Although there is concern over the structure of ECP, there has been no research to date showing a greater injury risk when compared to other recommended methods of exercise. Therefore, it is important to quantify the movement patterns and muscle activation in participants who have experience in exercise training during ECP exercises.

## 3. Specific Introduction

Resistance training protocols are distinguished by the number of reps, sets, loads, speed, and rest periods. Typically, shorter rest periods and longer sets are conducive to muscular endurance while longer rest periods and shorter sets are associated with strength and power gains (Kraemer et al., 1987). An example of a type of protocol that has gained significant popularity recently is the use of significantly shorter rest periods at a self-selected frequency while maintaining moderately heavy loads and high reps. Previous studies have referred to this style of training as ECP (Bergeron et al., 2011; Grier et al., 2013; Hooper et al., 2014). ECP are a relatively distinctive and widespread method of exercise conditioning, with CrossFit™ being the most prevalent example. Several reviews have identified the low back as the most common site for injury during ECP (Keogh & Winwood, 2017; Hak et al. 2013), but as detailed previously the increased rate of injury is not disproportionate relative to other exercise activities. Also, while there is a lack of research highlighting the mechanisms that are suspected to make ECP more dangerous than other widely accepted forms of exercise, findings of previous studies may explain some of the persistent concerns of ECP. Lattanzio et al. (2013) investigated the effects of muscular fatigue on knee joint proprioception. They evaluated eight men and eight women with no history of lower limb injures. They had three fatiguing protocols (ramp test, continuous test, and interval test) consisting of lower limb cycling on a computer-driven cycle ergometer. These authors found that exercising to fatigue may produce a change in participants ability to reproduce knee joint angles, representing a decline in proprioceptive function after heavy exercise bouts (Lattanzio et al., 2013). In addition, a biomechanical analysis of lifting was performed before and after fatiguing the quadriceps muscles by Traffimow et al. (1993). They evaluated how fatigued quadriceps muscles changed or altered the lifting technique from a squat lift (leg) to a more stoop (back) lift. They noticed fatigue significantly changed variables such as an increase in trunk angular velocity and a decrease in knee moment and hip angles (Traffimow et al., 1993). These results were consistent with the findings of Brown (1971) and NIOSH (1971), which have shown that the squat exercise requires larger amounts of energy to complete. Lifting objects from the floor has been extensively researched in a workplace setting (Marras et al. 1993), with a lack of research focusing on the deadlift and squat exercise in the general recreationally active adult population. As with many other complex movements, there is no universally agreed on perfect technique (Chaffin, 2006).  To date, only one study has examined the biomechanics of lifting during an ECP (Hooper et al., 2014). However, this study examined only the barbell back squat exercise and did not require participants to have prior experience with ECP, and it is known that experience impacts the performance in completing any task. Therefore, the purpose of this study was to examine the change in kinematics, muscle activation and discomfort in both the deadlift and squat in experienced ECP participants.

# 4. Methodology

## *4.1 Participants*

Ten males and ten females (mean=29.5 yrs ± 3.9) were recruited to participate in the study. Mean age, height and body mass for all participants are listed in Table 4.1. All participants were right-hand dominant and had not been treated for back, neck, or shoulder pain nor had had any other major injuries to any body part in the previous 2 years (i.e. compound fracture, laceration, etc.). The participants were all recruited from local ECP gyms in Vaughan, Ontario, Canada and were required to have at least 1 year of experience with ECP. Further, participants were required to have been involved in a resistance training program for a minimum frequency of 2x/week that included participation in exercises designed to condition the low back. Prior to the study, they were screened by a certified CrossFit™ coach, to ensure that they were able to complete the squat, deadlift, and shoulder press safely and with acceptable technique based on CrossFit™ standards (Glassman, 2003). While the workout consisted of the three aforementioned exercises, due to limitations of equipment sufficient motion capture volume could only be obtained for the deadlift and squat exercises, so these were chosen for analysis. Participants did not work out 48 hours prior to the collection to avoid any muscle soreness that would affect their performance or movement patterns. They were instructed to wear their usual sports shoes and to prepare for the protocol as they normally would for any regular workout of this nature. The entire data collection for a participant was completed on a single day. All procedures were approved by York University's Office of Research Ethics and informed consent was obtained from participants prior to participating in the study.

**Table 4.1:** Mean (±SD) of participant characteristics.

| Anthropometrics | Male (n=10) | Female (n=10) | All (n=20) |
|---|---|---|---|
| Age (years) | 30.7 ± 3.4 | 28.3 ± 4.1 | 29.5± 3.9 |
| Height (m) | 1.8 ± 0.1 | 1.7 ± 0.5 | 1.7 ± 0.1 |
| Body Mass (kg) | 83.7 ± 5.1 | 66.4 ± 9.6 | 75.1 ± 11.6 |

## *4.2 Experimental Set Up*

### *4.2.1 Muscle Activity*

Muscle activation was recorded from eight muscles bilaterally using pairs of disposable Ag/Ag-Cl surface electromyography (EMG) electrodes (Ambu Blue Sensor N, Ambu A/S, Denmark) placed apart with a centre-to-centre distance of 2.5 cm (Ambu® Blue Sensor N, Ambu A/S, Denmark). The skin was prepped by shaving hair and alcohol swabbing over electrode placement sites (McGill, 1991; Mirka and Marras, 1993; Drake et al., 2006; Nelson-Wong et al., 2008). Electrodes were adhered over the largest portion (~centre) of the muscle bellies to allow for the best observable signal (Gilmore & Meyers, 1983). Muscle activity was recorded using two AMT-8 EMG amplifier systems (Bortec Biomedical Ltd., Calgary, Canada). Activation was recorded from: thoracic erector spinae (TES); lumbar erector spinae (LES); rectus abdominis (RA); external obliques (EO); internal obliques (IO); gluteus medius (GM); biceps femoris (BF); and rectus femoris (RF) muscles (Figure 4.1 and Figure 4.2). The electrode placements for these muscles is detailed in Table 4.2 (Drake et al., 2006; McGill, 1991; Winter & Yack, 1987). These muscles were chosen due to their superficial nature for ease of recording and because they represent the major muscles involved in trunk, pelvis, and hip stabilization and movement. Two reference electrodes, one for each AMT-8 system, were placed on the left and right clavicles (Figure 4.1). EMG signals were differentially amplified (frequency response 10-1000 Hz, common mode rejection 115 dB at 60 Hz, input impedance 1000 G-Ω; model AMT-8, Bortec, Calgary, Canada) and converted at 2048 Hz (3DInvestigator, Northern Digital Inc., Waterloo, ON, Canada) from analog to digital form.

**Table 4.2:** Approximate electrode placements for the eight muscles tested (bilaterally). The electrodes were placed over the largest portion of the muscle belly to collect the muscle activation.

| **Muscle** | **Location** |
|---|---|
| Thoracic erector spinae | ~2.5 cm lateral to $T_9$ spinous process (McGill, 1991) |
| Lumbar erector spinae | ~3 cm lateral to $L_3$ spinous process (McGill, 1991) |
| Rectus abdominis | ~3 cm lateral to the umbilicus (McGill, 1991) |
| External oblique | ~15 cm lateral to umbilicus (McGill, 1991) |
| Internal oblique | Superior to inguinal ligament (McGill, 1991) |
| Gluteus medius | Midway between the GT and the sacrum (Winter & Yack, 1987) |
| Biceps femoris | Between ischial tuberosity and the lateral epicondyle of the tibia (Winter & Yack, 1987) |
| Rectus femoris | Midway between the ASIS and the superior borer of the patella (Winter and Yack 1987) |

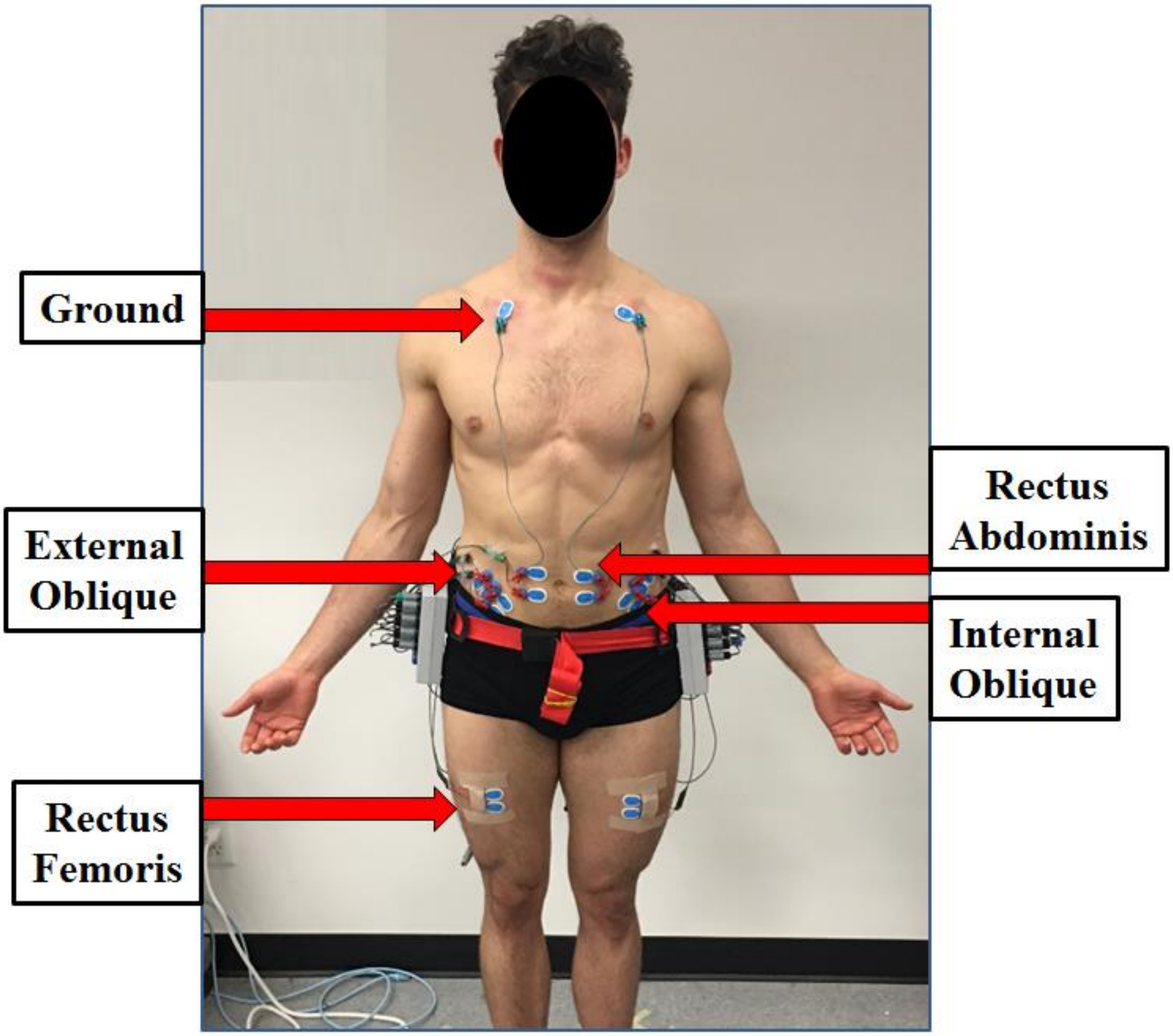

**Figure 4.1:** Anterior view of electrode placement for abdominal and thigh musculature. (RA: Rectus abdominis; EO; External oblique; IO: Internal oblique; RF: Rectus femoris). Note the position of the ground electrodes on the clavicles.

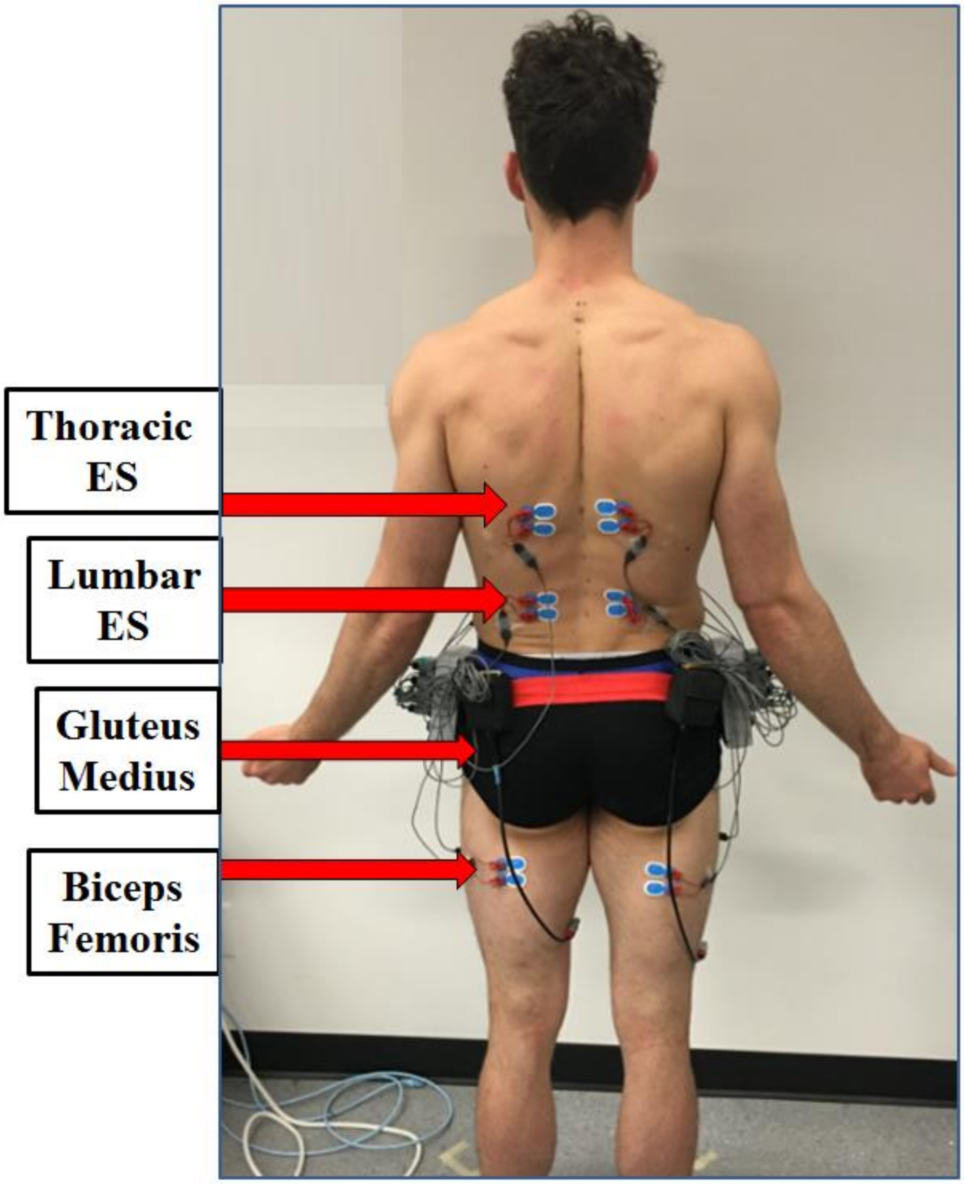

**Figure 4.2:** Posterior view of electrode placement for the back, thigh, and gluteus musculature. (TES: Thoracic erector spinae; LES: Lumbar erector spinae; GM: Gluteus medius; BF: Biceps femoris).

### *4.2.2 Kinematics*

Kinematic data were collected at 32 Hz using 3D Investigator ™ position sensors (Northern Digital Inc., Waterloo, Canada) and First Principles software (Northern Digital Inc., Waterloo, Canada). The position sensors detect infrared light emitted by the active markers

(IRED) placed on the participant. A total of 46 active markers were used and attached to rigid bodies (Northern Digital Inc., Waterloo, Canada) as well as custom rigid bodies. The trunk was subdivided into sections by four custom rigid bodies placed at $C_7$, $T_6$, $T_{12}$, and $S_2$. The custom rigid bodies placed on the spine consisted of 4 markers while all other rigid bodies were standard 3 marker rigid bodies (Figure 4.3). Tracking markers were placed on the head, trunk, arms, and legs (Figure 4.4) and a digitizing probe was used to determine the locations of specific landmarks relative to rigid bodies (Figure 4.5). There were 41 landmarks used to digitize segments, beginning with the head (left and right angle of jaw and temple; 4 total), arms (acromia, lateral shoulder joint spaces, lateral and medical epicondyles, ulnar and radial styloid; 12 total), trunk (acromia, sternum, $C_7$ vertebra, $T_6$ vertebra, $T_{12}$ vertebra, $S_2$ vertebra; 11 total) pelvis (iliac crests (IC), anterior superior iliac spines (ASIS), posterior superior iliac spines (PSIS); 6 total), and legs (greater trochanters (GT), lateral and medial knee epicondyle joint spaces, lateral and medical malleoli; 8 total). The segments included were: the head, neck, upper thoracic (UT), lower thoracic (LT), lumbar, trunk, and pelvis, thigh and shank. The joints included were: $C_7$, $T_6$, $T_{12}$, $S_2$, right and left hips, and right and left knees. Upright standing was used to define zero degree postures for the head, neck, trunk, and pelvis. To determine the 3D origin, a calibration cube was placed at a point on the floor and the global coordinate system was marked at this point with arrows. The axes and participants were aligned so that flexion/extension occurred in the Y axis, lateral bend in the X axis, and axial twist in the Z axis. Participants were instructed to align themselves in the direction of the arrows.

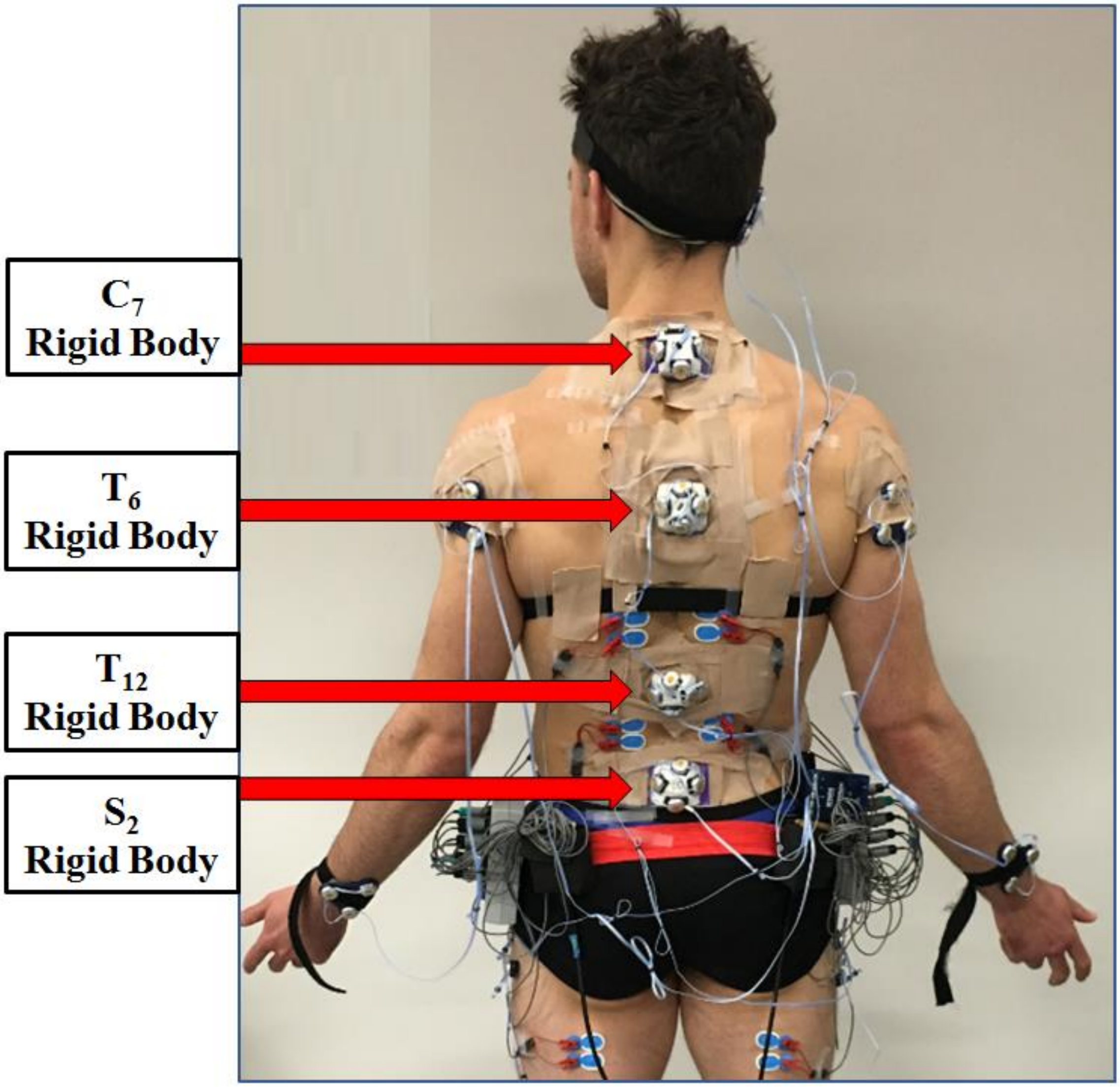

**Figure 4.3:** Posterior view of custom rigid bodies placed on the trunk at $C_7$, $T_6$, $T_{12}$, $S_2$.

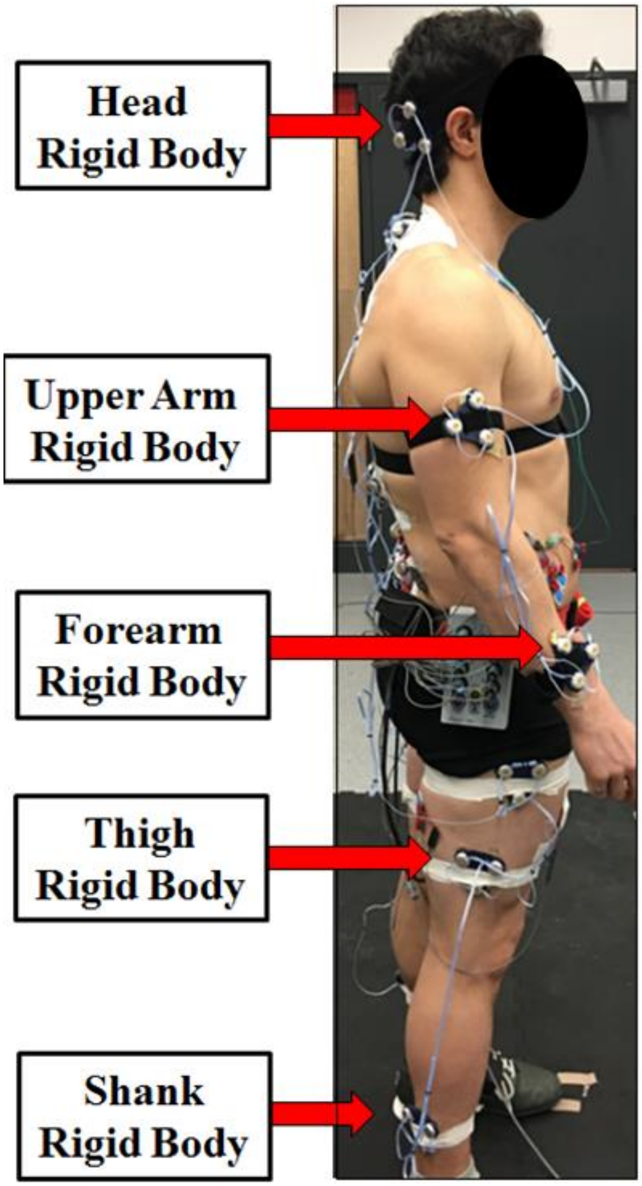
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**Figure 4.4:** Sagittal view of rigid body placement for full body tracking.

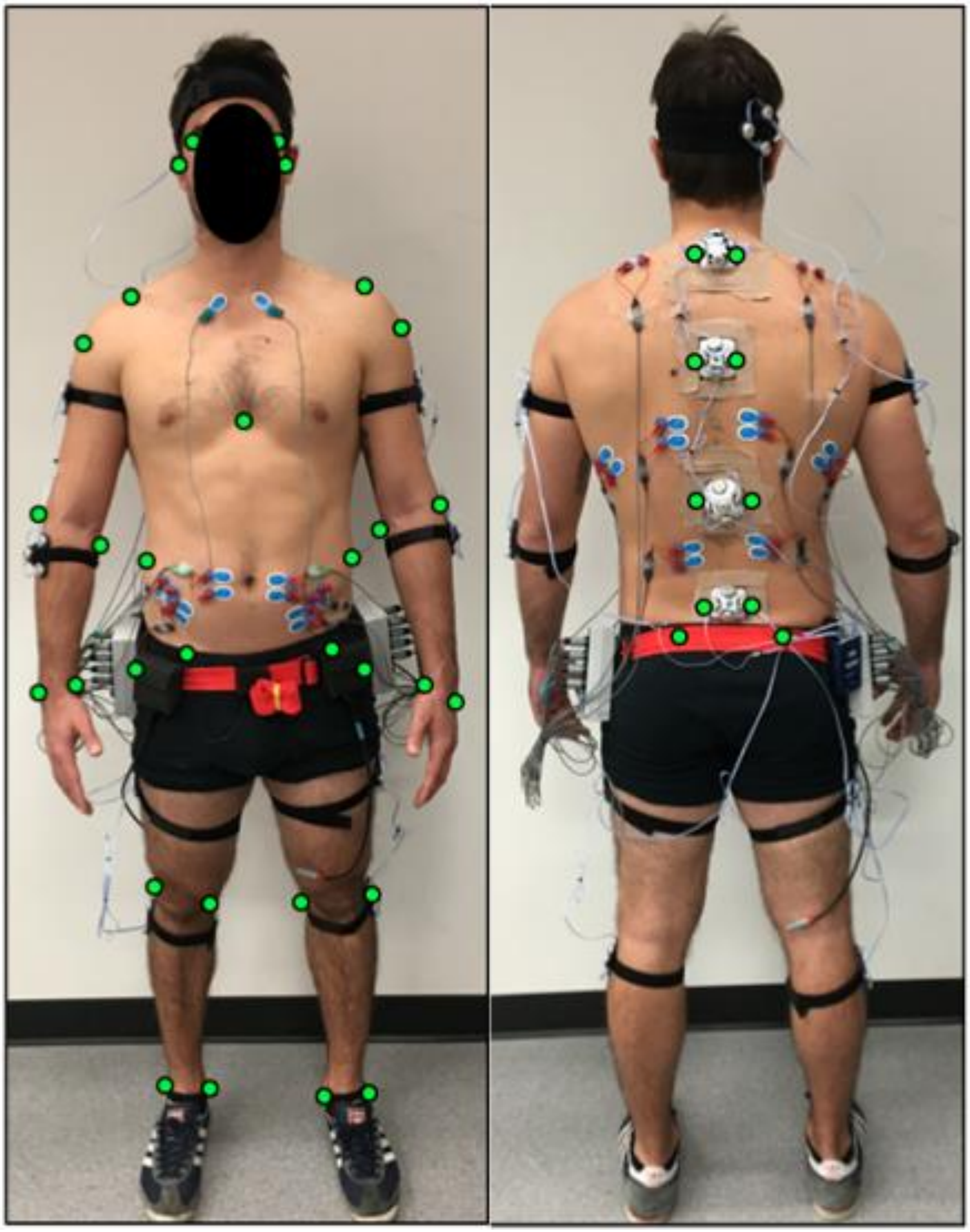

**Figure 4.5:** Visual representation of 41 digitized landmarks used as imaginary points to determine the distance of a rigid body to a segment.

### *4.2.3 Discomfort*

Participants recorded their perceived level of discomfort using a VAS, (Figure 4.6) as this scale has been shown to have validity and good repeatability (Summers, 2001). The VAS sheet used was a blank 100 mm scale, with two fixed anchor points labeled “no-pain” and “worst pain imaginable”. The VAS scale was recorded at the beginning of the study and after every round (5 rounds) for a total of 6 discomfort scores. The participants were given a fresh sheet every time (to avoid bias of previous rating) and they were asked to indicate, by a vertical mark across the line, the current back pain they were experiencing. Previous research has shown that a change of 10 mm indicates the development of clinically significant levels in pain (Nelson-Wong & Callaghan, 2008), so this cutoff was used to evaluate the participant responses.

**Figure 4.6:** Sample visual analog scale (VAS) score sheet (100 mm in length) on which participants indicated their level of pain.

### *4.2.4. Heart Rate*

Heart rate was measured using the Polar M400 GPS running watch (Polar Electro Inc., Lake Success, New York). The heart rate monitor consisted of a transducer worn around the chest that transmitted heart rate information to a wristwatch receiver held by the researcher in a nearby range. Heart rate was recorded from the beginning to the end of the protocol, to quantify participants' changes in intensity and to assess whether rest periods being utilized by the participants were sufficient for recovery.

### *4.3 Protocol*

Informed consent was obtained prior to beginning the study. Electrodes were placed on muscles of interest and participants were instructed to complete a five minute rest trial lying supine on a padded table. To facilitate normalization, maximum voluntary contractions (MVCs) of each muscle of interest were obtained (Mirka, 1991) and described in Table 4.3.

**Table 4.3:** Tasks used to elicit maximal muscle activation. All tasks were resisted manually by researchers. Note: Some tasks elicit the maximal activation for more than one muscle group.

| Muscle | MVC | Reference |
|---|---|---|
| Thoracic erector spinae<br>Lumbar erector spinae | Lying on the bench, back extension | McGill 1991 |
| Rectus abdominis<br>External oblique<br>Internal oblique | Sit-up position on the bench, perform crunch, bend, twist | McGill 1991 |
| Gluteus medius | Hip abduction in the side lying position | Nelson-Wong et al. 2008 |
| Rectus femoris | In the seated position, knees are bent to 90 degrees | Krishnan et al. 2011 |
| Biceps femoris | Lying on the bench, Knee flexed to 55 degrees | Rutherford et al. 2011 |

The maximal values for the abdominal muscles (RA, EO, IO) were obtained using a modified sit-up protocol. Participants were seated with their knees bent and feet flat on the padded table. Participants were braced around the upper chest and shoulders by the researcher and instructed to flex, laterally bend, and axially twist against the manual resistance provided

(McGill, 1992). Next, a modified back extension was used as the MVC protocol to collect the maximum contractions of the back extensor muscles (TES, LES). The back extension required participants to lay prone on the padded table with their anterior-superior iliac spines (ASIS) at the edge of the table and their upper body hanging over the edge. The researcher provided manual resistance against the shoulder blades as the participants tried to extend their upper body above the level of the table (McGill, 1992). To collect maximum contraction of the GM, participants lay on their side with their legs straight with their full body supported by the padded table. The researcher then placed their hands inferior and superior to the knee of the top leg and instructed the participant to raise that leg while keeping it straight (Nelson-Wong et al., 2008). The RF MVC was obtained by having participants sit upright on a table with the lower legs hanging off the edge. With the knee at 90° participants were instructed to straighten out their leg while researcher provided manual resistance to the anterior part of the ankles (Krishnan et al., 2011). Finally, the BF MVC was obtained by having the participants lying in the prone position with both knees bent at 55°. Participants were then instructed to bring their heels to their buttocks while the researcher provided manual resistance at the heels. For all MVC trials, participants were verbally encouraged and given a minimum of 3 min rest between MVC trials to help minimize the effects of fatigue (Schinkel-Ivy et al., 2015). The maximum value obtained from any of the three trials was chosen as the MVC.

The custom and standard rigid bodies were then applied to the participants using double-sided tape. These rigid bodies were placed on the head, $C_7$, $T_6$, $T_{12}$, $S_2$, right upper arm, right forearm, right thigh, right shank, and left upper arm, left forearm, left thigh, and left shank (Figure 4.3 and Figure 4.4). Then, the 41 landmark positions were digitized (Figure 4.5).

A quiet 30 s standing trial in the anatomical position was recorded to establish the neutral upright standing position. Next, participants were asked to stand with their feet shoulder width apart with their hands by their side as they move through their full range of spine motion in each plane: maximum flexion (MaxFlex), maximum lateral bend to the right and left, and maximum axial twist to the right and left. The ROM of the spine regions in each direction (flexion/extension, lateral bend, and axial twist) were measured to normalize all movement as percentage of each individual's ROM. Furthermore ROM was evaluated to certify that the joint angles obtained from the protocol correctly represented the kinematic measures. Participants were then instructed to complete a typical ECP (specific details below) consisting of three common exercises; the deadlift, squat and shoulder press. The shoulder press was included to make the workout typical of an ECP, but due to equipment limitations could not be quantified. A visual representation of these exercises are shown in the sagittal view (Figure 4.7) and the frontal view (Figure 4.8). The deadlift is an exercise where the participant is bending over and grasping a barbell that is lying on the floor. With straight arms, the participant then lifts the barbell off the ground and the rep is considered completed when the legs are straight, hips extended, and the entire body is vertical (Figure 4.7). The front squat exercise in this study begins with the participant standing upright holding the barbell across the upper chest and shoulders, with the elbows raised and the upper arms parallel to the ground (Figure 4.7). With a slight forward lean the participant lowers the body into a squat by bending at the knees until the thigh is parallel with the ground (Figure 4.8).

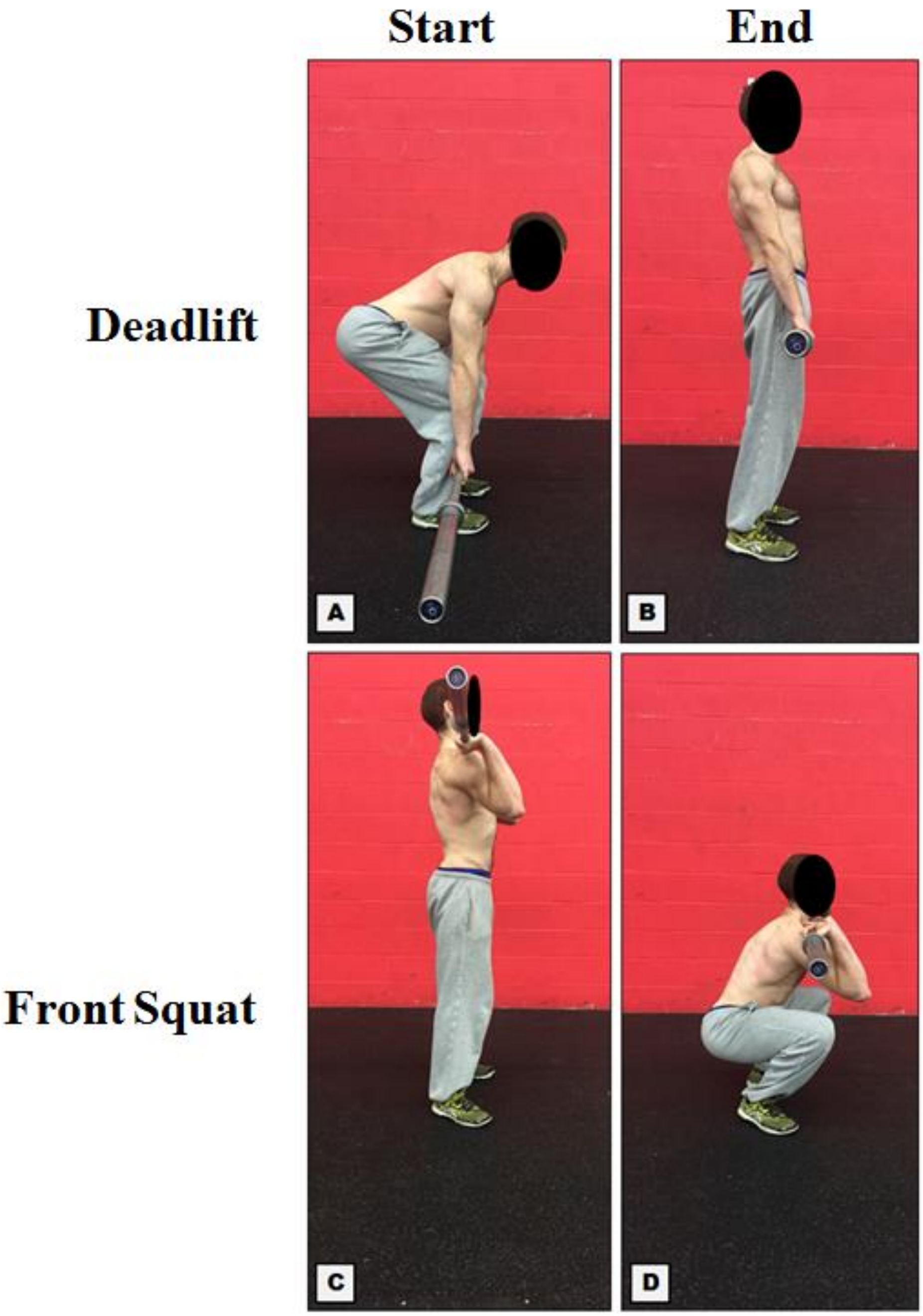

**Figure 4.7:** Sagittal view of the deadlift and the squat. **A** – Start of the deadlift. **B** – End of the deadlift. **C** – Start of the front squat. **D** – Bottom of the front squat.

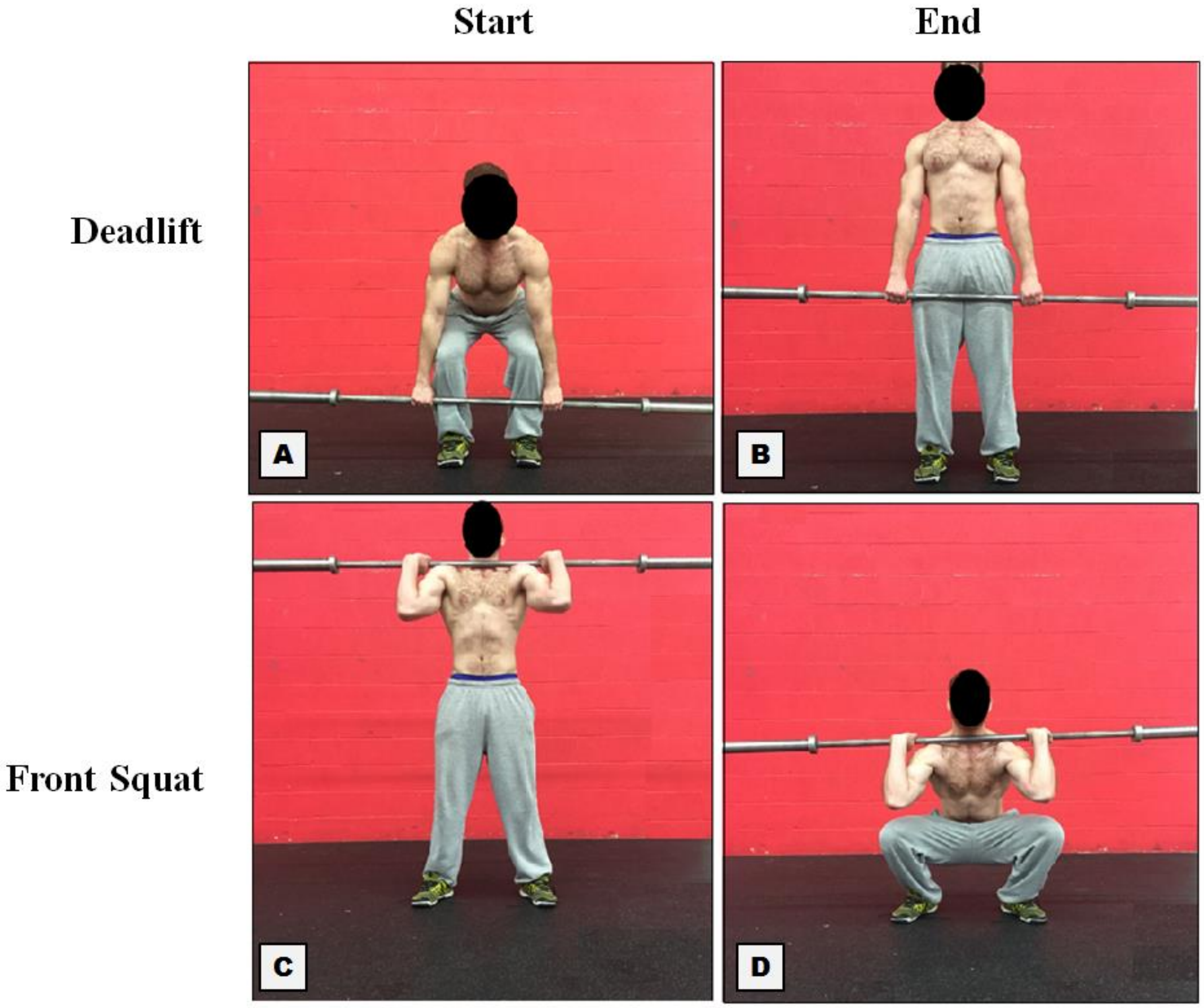

**Figure 4.8:** Frontal view of the deadlift and the squat. **A** – Start of the deadlift. **B** – End of the deadlift. **C** – Start of the front squat. **D** – Bottom of the front squat.

The shoulder press exercise begins with the participant standing upright, holding dumb bells in each arm at their shoulder. The participant raises the dumb bells vertically above their head until the arms are fully extended and the rep is completed when the participant returns the weight back to their shoulder position.

The weight for each participant was based on 60% of their self-reported 1RM. Again, the 1RM is the most weight a participant is capable of lifting in that exercise for a single rep. The structure of the workout required 8 reps of the deadlift, followed by 8 reps of the squat, and then

8 reps of the shoulder press. This is considered one round and the entire workout consisted of 5 rounds (Figure 4.9).

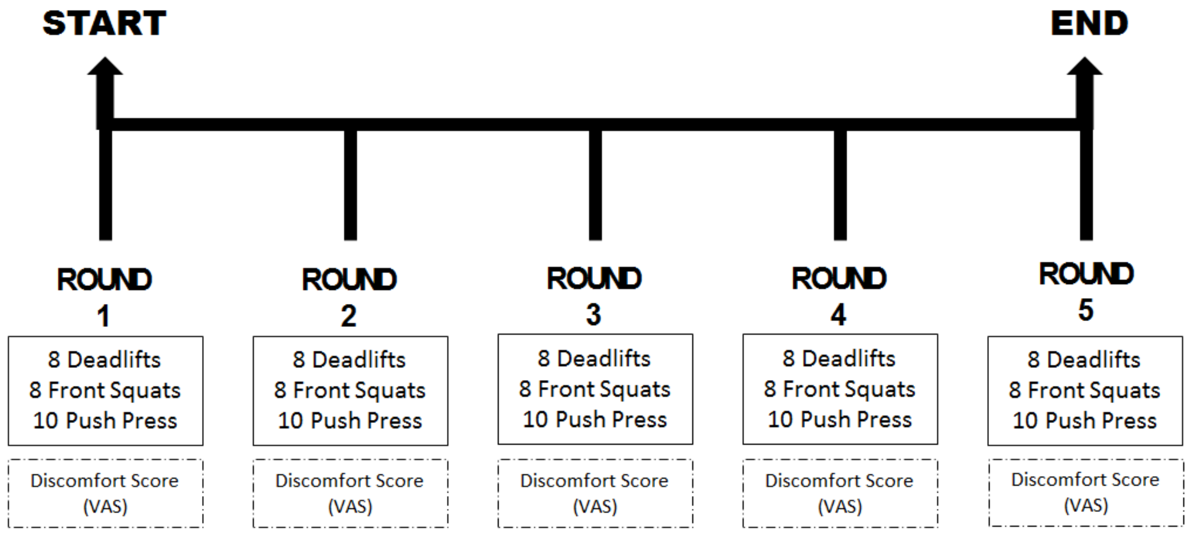

**Figure 4.9:** Timeline of the extreme conditioning protocol. Participants completed three different exercises (deadlift, front squat, push press) at weights of 60% of their 1 RM (maximum repetition).

Instructions were to complete 5 rounds as quickly as possible while maintaining proper technique. Since the participants were familiar with this type of direction no further instructions were required. The frequency and duration of rest periods was left to the discretion of the participant, as they were instructed to treat this as a regular ECP workout. Figure 4.10 shows the experimental set up for a participant during the ECP.

**Figure 4.10:** Visual representation of the starting position of the deadlift (left) bottom of the front squat (right).

## *4.4 Data Processing*

### *4.4.1 Muscle Activity*

All data processing for EMG data was accomplished using Visual3D v.5 software (C-Motion Inc., Germantown, MD). EMG was high pass filtered at 30 Hz to remove electrocardiogram contamination (Drake and Callaghan, 2006). Filtered data was full wave rectified and passed through a fourth-order low-pass, dual-pass Butterworth filter, producing a linear envelope signal for each of the 16 muscles recorded (Brereton and McGill, 1998). The signals were normalized to a percent of maximum muscle activation (%MVC), using the maximum values from the MVC trials. Using the normalized EMG data, the maximum, minimum, and range of activation for each trial were quantified.

### *4.4.2 Kinematics*

Using Visual 3D v.5 software (C-Motion Inc., Germantown, MD), the kinematic data were low-pass filtered with a dual-pass, fourth-order Butterworth filter with a cutoff frequency of 2.5 Hz (Winter, 2005). The mean angles during the upright stand were calculated and used to zero the angles from the trials (remove the angular bias associated with standing specific to each participant). All spine angles were reported as a percentage of each participants maximum 3D ROM, which was measured at the beginning of the protocol. This was done to account for the variations in flexibility of participants and also to examine how close a participant was to their end ROM during the completion of the ECP. The bottom position in both the squat and deadlift were compared within each exercise and between rounds. This position was chosen because it is a repeatable position that provides a good basis for comparison. The bottom of the squat was defined as the frame in which the vertical velocity of the participant's centre of mass reached zero. With regards to the deadlift, the bottom of the deadlift was signaled by the first frame of vertical movement of the barbell. An average angle for each segment and joint among all participants were taken for each round and each round was compared to determine whether changes were occurring as the participant progressed through the workout.

### *4.4.3 Discomfort*

The discomfort score was taken from the beginning of the ECP (using the 100mm VAS), and this was used as the baseline to be subtracted from all other scores to remove bias. The average discomfort scores were taken for each round to enable the ability to track any changes over the course of the protocol.

#### *4.4.4. Heart Rate*

Mean heart rates values were taken for each round to investigate any changes over the course of the protocol. The maximum heart rate was determined by using Equation 4.1 (ACSM, 2015). Heart rate data was then normalized as a percentage of each participant's age predicted maximum heart rate (Equation 4.2).

Equation 4.1 $$\text{Max HR} = 220 - \text{Age (years)}$$

Equation 4.2 $$\text{Normalized Heart Rate} = \left(\frac{Heart\ rate}{Max\ HR}\right) * 100\%$$

### *4.5 Data Analysis*

A three way repeated measures analysis of variance (ANOVA) using SAS 9.3 (SAS Institute Inc., Cary, NC, USA) was used to analyze muscle activity, kinematics, discomfort score, and heart rate with repeated measures of rounds (five levels: one, two, three, four, five), side (two levels: left and right) and between-group factors of sex. Where there were no significant effects involving these factors, the data were collapsed. When the assumption of sphericity was not met, degrees of freedom were determined using the Huynd-Feldt corrections. Alpha was set to 0.05 and significant *F*-tests were evaluated using Tukey's post-hoc to establish whether any of the trial rounds demonstrated significant differences form others. A statistician from York University was consulted prior to the proposal for guidance on using appropriate analyses for this study.

## 5. Results

### *5.1 Muscle Activity*

Muscle activity during the ECP was evaluated in this study. Muscle activation levels for the deadlift were between (6-32 %MVC) and muscle activation levels for the squat were between (7-39 %MVC). A summary of statistical analysis of the muscles is shown in Table 5.1. Detailed tables in Appendix A shows mean muscle activity levels of the deadlift (Table A1) and the squat (Table A2) throughout the protocol, as well a listing of all of the statistical results (Tables A3-A5).

**Table 5.1:** Summary of statistical analysis results of mean muscle activity (%MVC) during the deadlift and squat. The number of rounds were the main effect, with significant values ($p<0.05$) denoted with shading.

| **Round** | **Deadlift Exercise**<br>*F*-Statistic | **Squat Exercise**<br>*F*-Statistic |
|---|---|---|
| RA | **$F_{4,76}=2.62$, $p=0.04$** | $F_{4,76}=0.64$, $p=0.64$ |
| IO | $F_{4,76}=2.09$, $p=0.09$ | $F_{4,76}=1.13$, $p=0.35$ |
| EO | $F_{4,76}=1.54$, $p=0.19$ | $F_{4,76}=1.78$, $p=0.14$ |
| BF | $F_{4,76}=2.09$, $p=0.09$ | $F_{4,76}=0.04$, $p=0.99$ |
| RF | $F_{4,76}=1.89$, $p=0.12$ | $F_{4,76}=0.84$, $p=0.51$ |
| GM | $F_{4,76}=1.6$, $p=0.18$ | $F_{4,76}=0.95$, $p=0.44$ |
| TES | **$F_{4,76}=4.33$, $p=0.003$** | **$F_{4,76}=2.99$, $p=0.02$** |
| LES | **$F_{4,76}=4.86$, $p=0.002$** | **$F_{4,76}=4.04$, $p=0.005$** |

There were no main effects of sex and side for all muscles during the deadlift ($F_{1,18}=0.01$, $p=0.98$) and the squat ($F_{1,18}=0.36$, $p=0.83$). This indicates that the men and women were able to perform the tasks using similar symmetric muscle activation. Likewise, the data were collapsed across sex and side and an ANOVA was run on the rounds (1-5). No interactions were found between the rounds, however, significant changes were observed in the TES, LES, and RA in both the deadlift and squat exercises (Table 5.1). More specifically, during the deadlift (Figure 5.1), LES showed a difference in mean muscle activation between rounds 1 and 4 as well as 1 and 5 ($F_{4,76}$=4.86, *p*=0.002). TES showed a difference between rounds 1 and 4 ($F_{4,76}$=4.33, *p*=0.003), and the RA showed significant differences between rounds 1, 3, 4, and 5 ($F_{4,76}$=2.62,*p*=0.04). These data indicate that significant muscle activation changes occurred between the start of the workout and the end of the workout. In addition, the LES muscles showed higher activation at the start of the ECP in round 1 during the deadlift compared to the TES and RA. However, in round 5, TES muscles showed greater activation than the LES muscles (Figure 5.1).

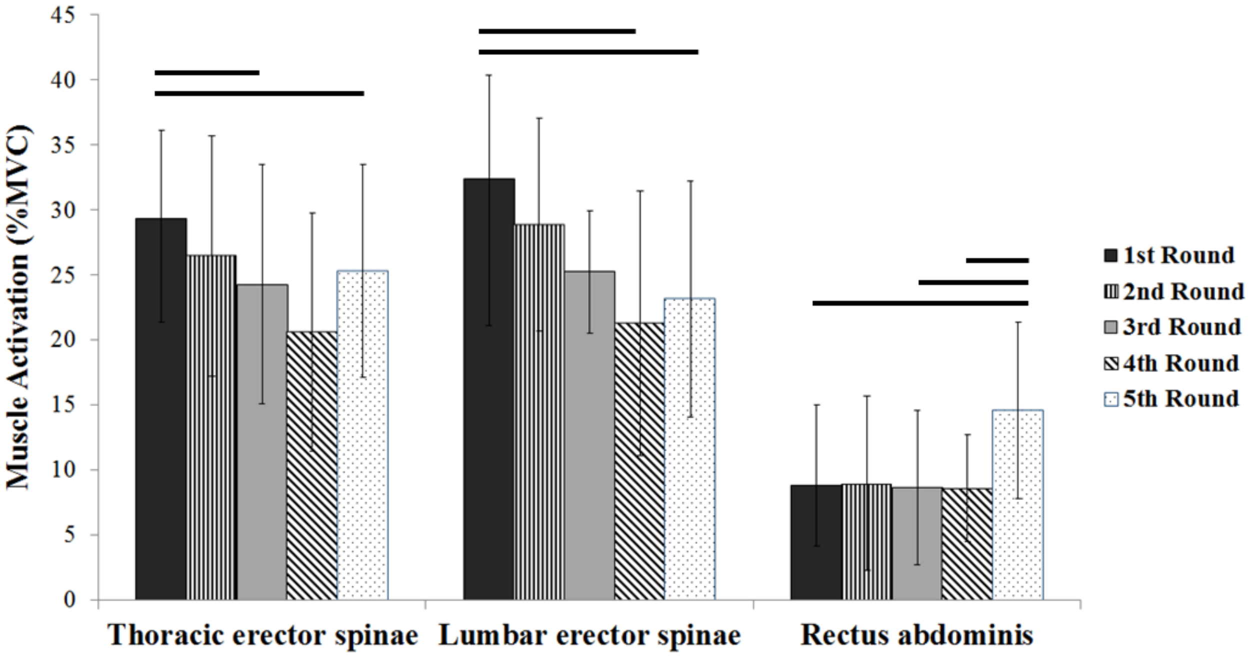

**Figure 5.1:** Mean (±SD) normalized activation of the trunk muscles during the deadlift. There are significant changes in the lumbar erector spinae muscles, thoracic erector spinae muscles, and rectus abdominis at the start of the ECP (1st round) compared to last round (5th round). Ends of horizontal bars indicate significant differences between rounds (p<0.05). For a detailed description of differences between rounds, refer to Table 5.2.

During the squat, LES showed significant differences between rounds 1 and 3 as well as 1 and 4 ($F_{4,76}$=4.04, *p*=0.005)(Figure 5.2). TES showed significant differences between rounds 2 and 4 ($F_{4,76}$=2.99, *p*=0.02). Similar to the deadlift, muscle activation changes during the squat were observed between the start and end of the workout. In addition, the TES muscles showed higher activation than the LES muscles during the squat.

**Table 5.2:** Pairwise comparisons of Tukeys *post-hoc* were used to establish whether any of the rounds for the spine muscles during the deadlift and squat demonstrated significant differences from others. Shaded cells indicate a significant difference between rounds within the same muscle (p<0.05). TES: thoracic erector spinae; LES: lumbar erector spinae; RA: rectus abdominis muscles.

| **Muscle** | **Rounds** | **Deadlift *p*-value** | **Squat *p*-value** |
|---|---|---|---|
| TES | 1 to 2 | 0.18 | 0.84 |
| | 1 to 3 | **0.02** | 0.08 |
| | 1 to 4 | 0.07 | **0.01** |
| | 1 to 5 | **0.001** | 0.08 |
| | 2 to 3 | 0.31 | 0.5 |
| | 2 to 4 | 0.08 | **0.006** |
| | 2 to 5 | 0.6 | **0.05** |
| | 3 to 4 | 0.1 | 0.4 |
| | 3 to 5 | 0.62 | 0.98 |
| | 4 to 5 | 0.31 | 0.41 |
| LES | 1 to 2 | 0.22 | 0.32 |
| | 1 to 3 | 0.07 | 0.009 |
| | 1 to 4 | **0.002** | **0.001** |
| | 1 to 5 | **0.001** | 0.8 |
| | 2 to 3 | 0.21 | 0.07 |
| | 2 to 4 | 0.07 | 0.2 |
| | 2 to 5 | 0.08 | 0.1 |
| | 3 to 4 | 0.17 | 0.61 |
| | 3 to 5 | 0.48 | 0.85 |
| | 4 to 5 | 0.51 | 0.48 |
| RA | 1 to 2 | 0.96 | 0.14 |
| | 1 to 3 | 0.95 | 0.24 |
| | 1 to 4 | 0.75 | 0.18 |
| | 1 to 5 | **0.01** | 0.06 |
| | 2 to 3 | 0.9 | 0.71 |
| | 2 to 4 | 0.79 | 0.08 |
| | 2 to 5 | 0.34 | 0.51 |
| | 3 to 4 | 0.7 | 0.45 |
| | 3 to 5 | **0.008** | 0.44 |
| | 4 to 5 | **0.03** | 0.21 |

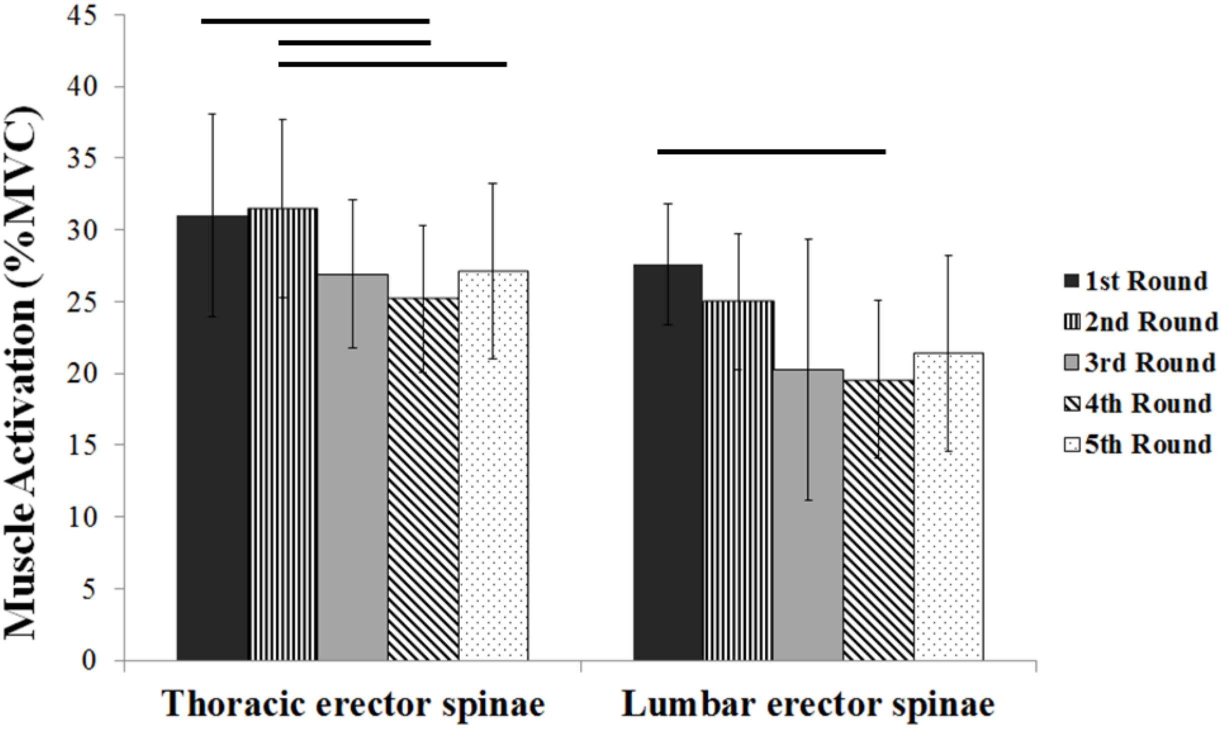

**Figure 5.2:** Mean (±SD) normalized activation of the trunk muscles during the squat. There are significant changes in the lumbar erector spinae muscles and thoracic erector spinae muscles. TES muscles appear to be more activated during the squat than LES muscles. Ends of horizontal bars indicate significant differences between rounds ($p<0.05$). For a detailed description of differences between rounds, refer to Table 5.2.

### *5.2 Kinematics*

The absolute mean angles (flexion/extension, lateral bend, axial twist) and relative mean angles (flexion/extension, lateral bend, axial twist) during the deadlift and squat were evaluated in this study and a detailed list of all the kinematics and statistical analyses values are in the tables in Appendix A (Tables A6-A16). There were no main effects of sex for the kinematics during the deadlift ($F_{1,18}=0.02$, $p=0.88$) and the squat ($F_{1,18}=0.03$, $p=0.91$). Therefore, the data were collapsed across sex and an ANOVA was run on the rounds ($1^{st}$ to $5^{th}$). In addition, no interactions were found between the rounds ($F_{4,72}=0.22$, $p=0.93$).

Figure 5.3 displays the average flexion angle during the deadlift of the UT and LT region as a % of MaxFlex. Significant differences were found in UT and LT region during the deadlift (Table 5.3, Table 5.4). Specifically, flexion of the UT range was from 44.2% ± 3.7 to 51.2 % ± 1.4 and significant differences were found in the 1st, 2nd, 4th, and 5th round ($F_{4,66}$=3.64, *p*=0.009). The average LT flexion in the 1st round, is significantly different than the 3rd and 5th round ($F_{4,66}$=3.07, *p*=0.02) ranging from 63% ± 6.4 to 67.2% ± 8.6. Both UT and LT segments display an increase in forward lean in the 5th round when compared to the 1st round.

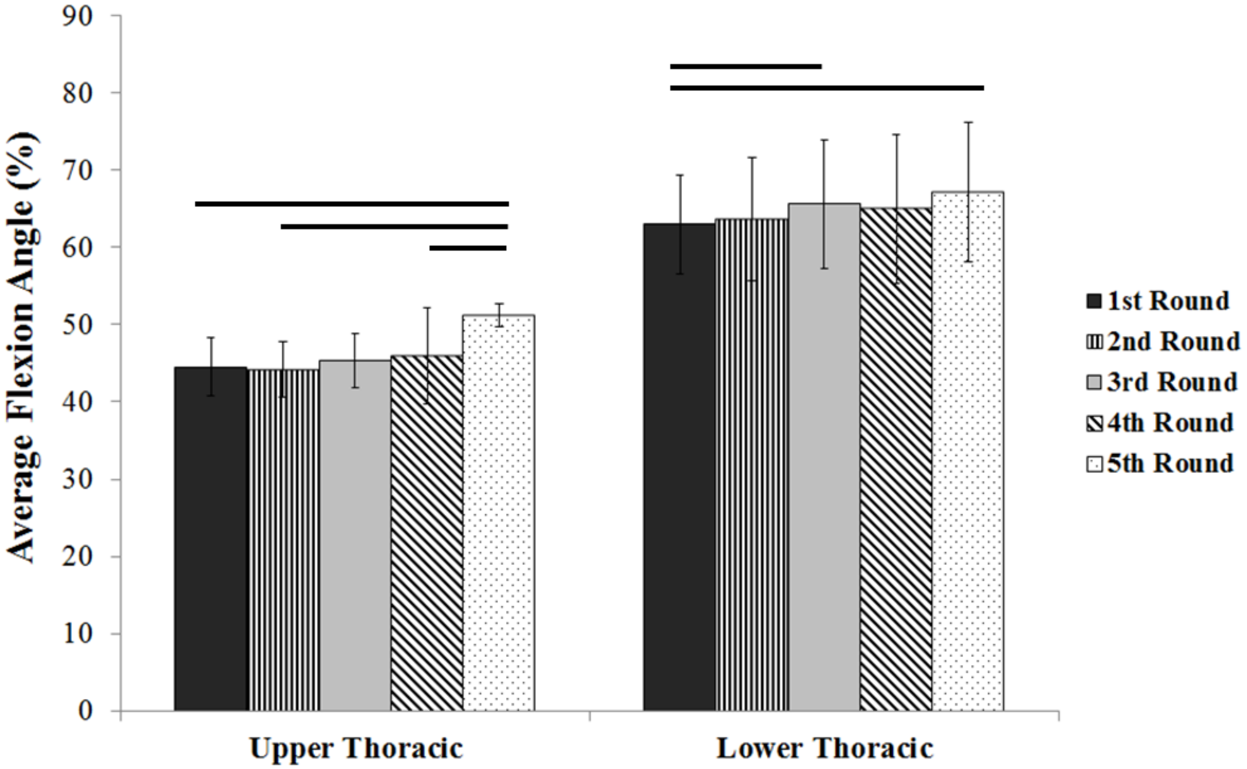

**Figure 5.3:** During the deadlift, flexion in the upper thoracic and lower thoracic increased significantly by the last round (5th round). Ends of horizontal bars indicate significant differences between rounds (p<0.05). For a detailed description of differences between rounds, refer to Table 5.4.

The average flexion angle during the squat of the UT, LT, and lumbar region are represented as a % of MaxFlex in Figure 5.4. During the squat, the average UT flexion in the 2nd round is significantly different than the 5th round ($F_{4,66}$=2.61, *p*=0.04). The UT range was from

18.3% ± 1.1 to 17.1% ± 1.7. The average LT flexion angle in the 1st round is significantly different than the 3rd and 5th round ($F_{4,66}$=7.33, $p$<0.001). The LT range is from 28.5% ± 1 to 25.4% ± 1.2. Lastly, the lumbar flexion range was from 28.7% ± 6.8 to 21.5% ± 1.2 with the 1st round being significantly different than the 3rd, 4th, and 5th round ($F_{4,66}$=17.04, $p$<0.001). Contrary to the deadlift, participants showed a decrease in flexion (or a more upright posture) during the squat as the protocol progressed from the 1st to the 5th round.

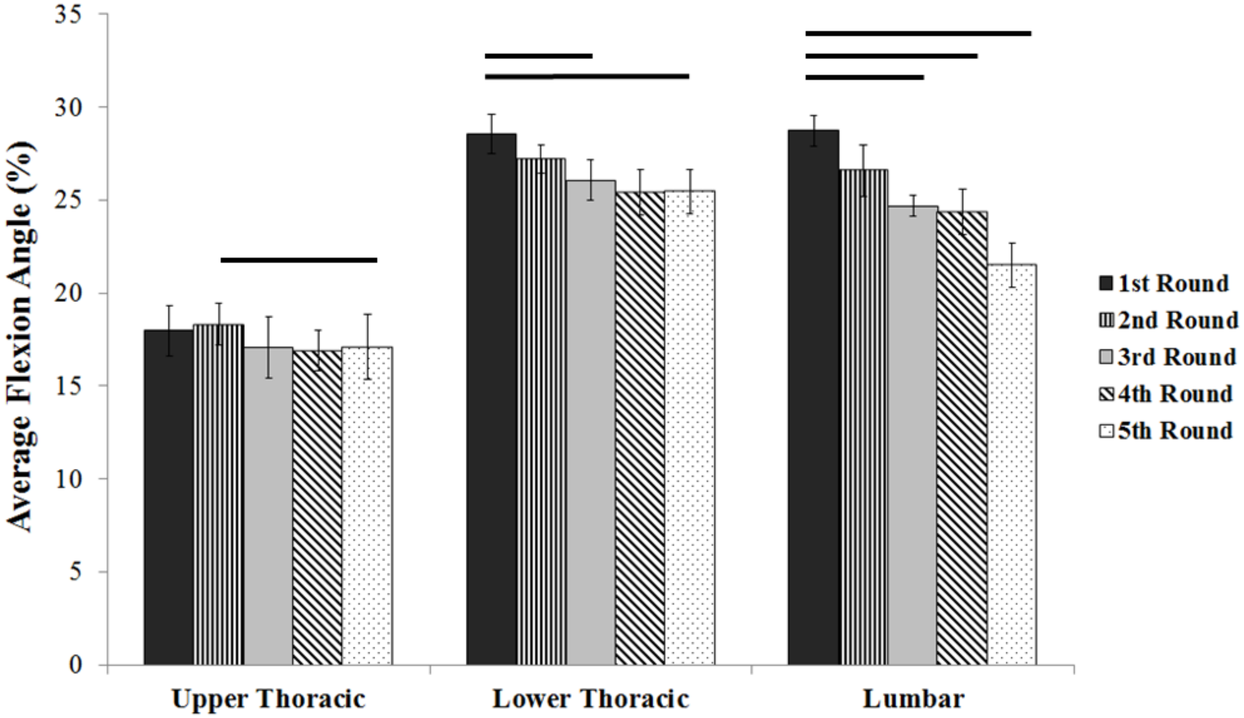

**Figure 5.4:** During the squat, flexion in the upper thoracic, lower thoracic, and lumbar decreased by the last round (5th round). Ends of horizontal bars indicate significant differences between rounds (p<0.05). For a detailed description of differences between rounds, refer to Table 5.4.

**Table 5.3:** Summary of statistical analysis results for mean trunk angle measures (expressed as a % MaxFlex) during the deadlift and squat. The number of rounds were the main effect, with significant values ($p<0.05$) denoted shading.

| **%ROM**<br>**AA** | **Deadlift Exercise**<br>*F*-Statistic | **Squat Exercise**<br>*F*-Statistic |
|---|---|---|
| Upper Thoracic | **$F_{4,66}$=3.64, $p$=0.009** | **$F_{4,66}$=2.61, $p$=0.04** |
| Lower Thoracic | **$F_{4,66}$=3.07, $p$=0.02** | **$F_{4,66}$=7.33, $p$<0.001** |
| Lumbar | $F_{4,66}$=1.57, $p$=0.19 | **$F_{4,66}$=17.04, $p$<0.001** |
| Trunk | $F_{4,66}$=1.35, $p$=0.26 | **$F_{4,66}$=3.7, $p$=0.008** |

**Table 5.4:** A pairwise comparisons of Tukeys *post-hoc* were used to establish whether any of the rounds for the spine segments (% MaxFlex) during the deadlift and squat demonstrated significant differences from others. Shaded cells indicate a significant difference between rounds within the same muscle (p<0.05).

| **Segment** | **Rounds** | **Deadlift**<br>***p*-value** | **Squat**<br>***p*-value** |
|---|---|---|---|
| Upper Thoracic | 1 to 2 | 0.63 | 0.43 |
| | 1 to 3 | 0.45 | 0.51 |
| | 1 to 4 | 0.51 | 0.14 |
| | 1 to 5 | **0.009** | 0.06 |
| | 2 to 3 | 0.79 | 0.1 |
| | 2 to 4 | 0.26 | 0.43 |
| | 2 to 5 | **0.002** | **0.01** |
| | 3 to 4 | 0.16 | 0.62 |
| | 3 to 5 | 0.12 | 0.93 |
| | 4 to 5 | **0.04** | 0.66 |
| Lower Thoracic | 1 to 2 | 0.89 | 0.08 |
| | 1 to 3 | **0.01** | **0.002** |
| | 1 to 4 | 0.29 | 0.7 |
| | 1 to 5 | **0.01** | **<.0001** |
| | 2 to 3 | 0.12 | 0.07 |
| | 2 to 4 | 0.34 | 0.22 |
| | 2 to 5 | 0.1 | 0.34 |
| | 3 to 4 | 0.17 | 0.64 |
| | 3 to 5 | 0.79 | 0.22 |
| | 4 to 5 | 0.11 | 0.44 |
| Lumbar | 1 to 2 | 0.7 | 0.21 |
| | 1 to 3 | 0.27 | **<.0001** |
| | 1 to 4 | 0.09 | **<.0001** |
| | 1 to 5 | 0.06 | **<.0001** |
| | 2 to 3 | 0.47 | 0.13 |
| | 2 to 4 | 0.19 | 0.23 |
| | 2 to 5 | 0.08 | 0.18 |
| | 3 to 4 | 0.56 | 0.96 |
| | 3 to 5 | 0.29 | 0.22 |
| | 4 to 5 | 0.64 | 0.31 |

With regards to the deadlift exercise, flexion in the left hip decreased from 112.5° ± 14.4 to 102.7° ± 14.3 in the 5th round from the 1st and 2nd round ($F_{4,76}$=6.51, *p*=0.001), and flexion in the right hip decreased from 108.8° ± 19.5 to 102.7° ± 14.3 in the 5th round from the 1st and 2nd round (Figure 5.3). Although not significant, the knee angles also decreased in the 5th round from 1st round, ranging from 68.6° ± 19.6 to 71.5° ± 20. These results indicate that the participants' began to straighten their legs during the deadlift as the rounds progressed (change their form).

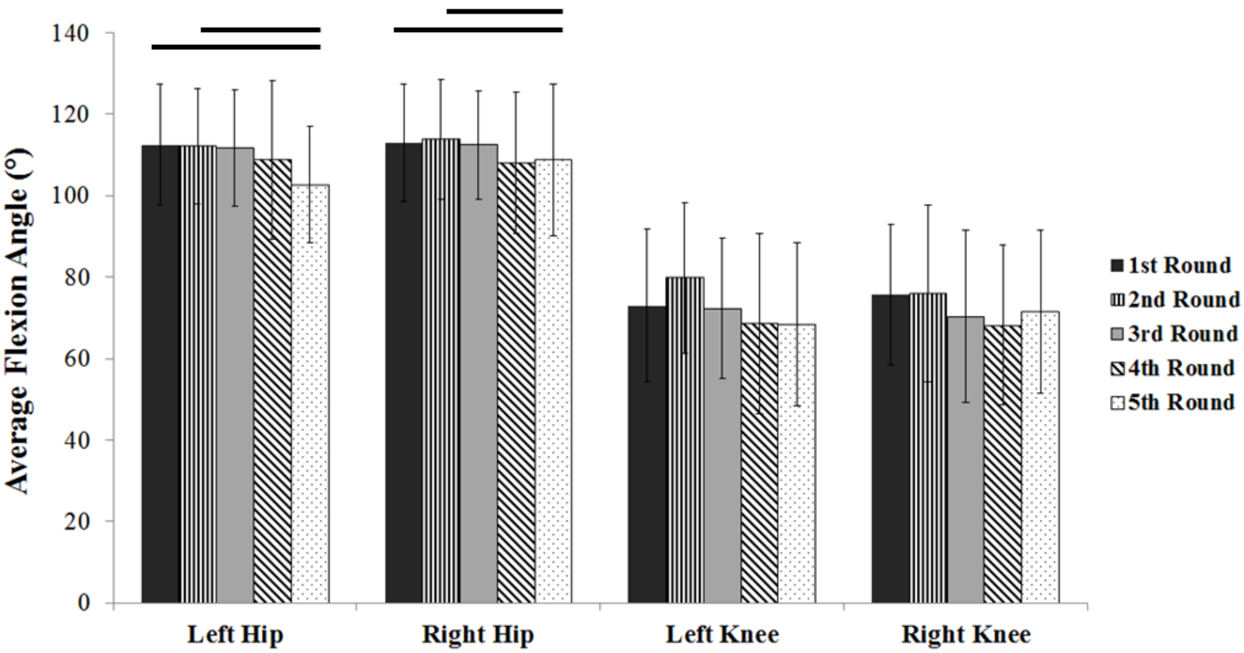

**Figure 5.5:** Hip and knee angles (°) for each round during the deadlift. Hip flexion decreased from the start of the workout (1st round) to the last round (5th round). Ends of horizontal bars indicate significant differences between rounds (p<0.05). For a detailed description of differences between rounds, refer to Table 5.5.

**Table 5.5:** A pairwise comparisons of Tukeys *post-hoc* were used to establish whether any of the rounds for the hip and knee joints during the deadlift and squat demonstrated significant differences from others. Shaded cells indicate a significant difference between rounds within the same muscle (p<0.05).

| Joint | Rounds | Deadlift *p*-value | Squat *p*-value |
|---|---|---|---|
| *Right side* | | | |
| Hip | 1 to 2 | 0.95 | 0.22 |
| | 1 to 3 | 0.81 | 0.18 |
| | 1 to 4 | 0.17 | **0.04** |
| | 1 to 5 | **0.01** | **0.002** |
| | 2 to 3 | 0.84 | 0.89 |
| | 2 to 4 | 0.14 | 0.49 |
| | 2 to 5 | **0.01** | 0.06 |
| | 3 to 4 | 0.1 | 0.57 |
| | 3 to 5 | 0.07 | 0.08 |
| | 4 to 5 | 0.24 | 0.14 |
| Knee | 1 to 2 | 0.37 | 0.97 |
| | 1 to 3 | 0.14 | 0.75 |
| | 1 to 4 | 0.06 | 0.67 |
| | 1 to 5 | 0.08 | 0.43 |
| | 2 to 3 | 0.57 | 0.77 |
| | 2 to 4 | 0.08 | 0.69 |
| | 2 to 5 | 0.25 | 0.42 |
| | 3 to 4 | 0.22 | 0.91 |
| | 3 to 5 | 0.51 | 0.59 |
| | 4 to 5 | 0.62 | 0.67 |
| *Left side* | | | |
| Hip | 1 to 2 | 0.38 | 0.18 |
| | 1 to 3 | 0.81 | 0.07 |
| | 1 to 4 | 0.06 | **0.001** |
| | 1 to 5 | **<.0001** | **0.002** |
| | 2 to 3 | 0.51 | 0.34 |
| | 2 to 4 | 0.06 | 0.3 |
| | 2 to 5 | **0.001** | 0.06 |
| | 3 to 4 | 0.1 | 0.21 |
| | 3 to 5 | 0.09 | 0.33 |
| | 4 to 5 | 0.13 | 0.78 |
| Knee | 1 to 2 | 0.88 | 0.26 |
| | 1 to 3 | 0.78 | 0.16 |
| | 1 to 4 | 0.07 | **0.001** |
| | 1 to 5 | 0.09 | **0.02** |
| | 2 to 3 | 0.9 | 0.81 |
| | 2 to 4 | 0.1 | 0.07 |
| | 2 to 5 | 0.13 | 0.1 |
| | 3 to 4 | 0.12 | 0.32 |
| | 3 to 5 | 0.15 | 0.13 |
| | 4 to 5 | 0.99 | 0.46 |

During the squat, changes in hip angles were also observed (Figure 5.4). Flexion in the left hip increased from the 1st round from 7.1° ± 9.6 to 9.5° ± 10.9 in the 5th round ($F_{4,76}$=3.92, *p*=0.007). Flexion in the right hip increased from the 1st round from 7.9° ± 9.6 to 9.7° ± 7.3 in the 5th round ($F_{4,76}$=2.81, *p*=0.03). In addition, the average left knee flexion increased from the 1st round from 4.7° ± 11.6 to 6.2° ± 14.4 in the 5th round ($F_{4,76}$=3.7, *p*=0.01), indicating participants had a greater knee bend in the 5th rounds compared to the 1st round.

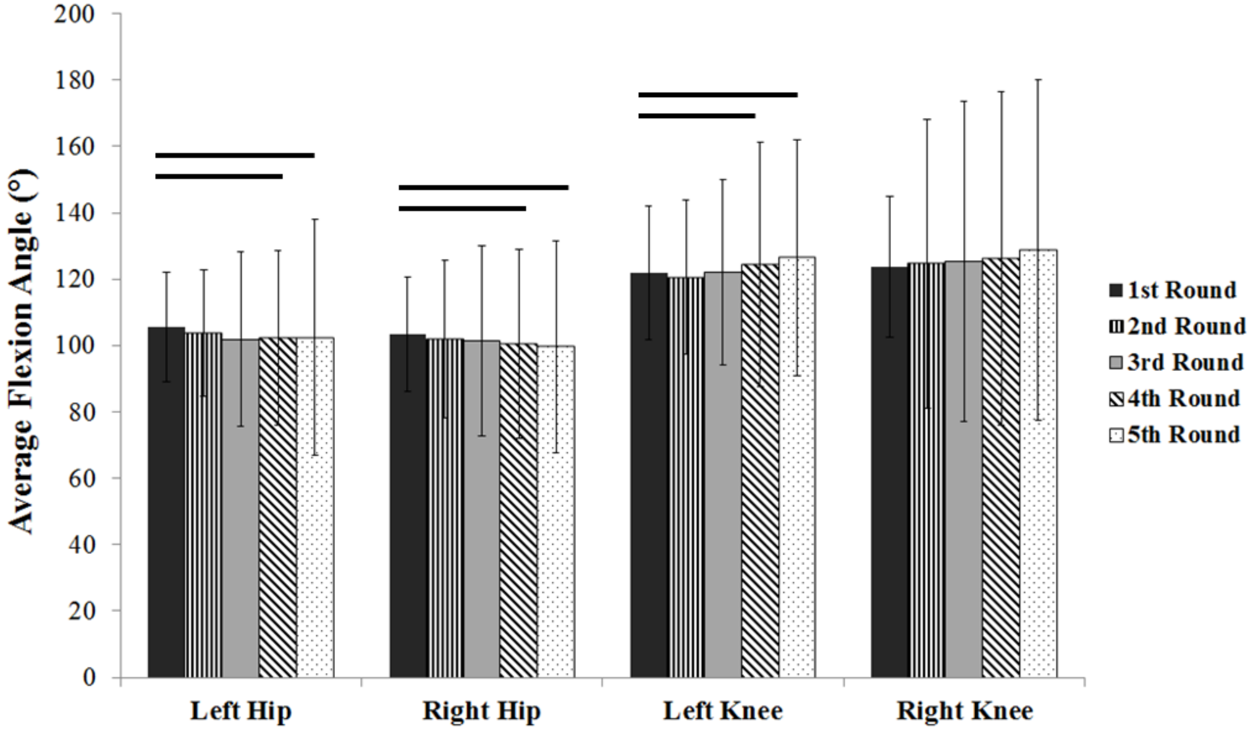

**Figure 5.6:** Hip and knee angles (°) for each round during the squat. Hip and knee flexion increased from the start of the workout (1st round) to the last round (5th round). Ends of horizontal bars indicate significant differences between rounds (p<0.05). For a detailed description of differences between rounds, refer to Table 5.5.

### *5.3 Discomfort*

There was a difference found in discomfort score between each round ($F_{4,95}$=13.57, *p*<0.001). Participants' discomfort score showed significant increases throughout the protocol at each round (Figure 5.7). Recall, a discomfort score rating above 10 mm is considered to be the development of clinical relevant pain (Nelson-Wong et al., 2008), and this was demonstrated in the 4th and 5th round. Discomfort ratings increased from 0.65mm ± 0.5 in the 1st round to 15.6mm ± 12.3 in the 5th round. It is important to note that participants were not asked to distinguish between the types of discomfort (muscle fatigue vs. muscle strain). To show the changes in discomfort ratings per round, the relative change in discomfort ratings was graphed. The statistical increases in the 4th and 5th rounds as noted above can be clearly observed in Figure 5.8. It is important to note that participants were not asked to distinguish between types of pain. Also, participants were not asked for a discomfort score post testing (after the equipment was taken off).

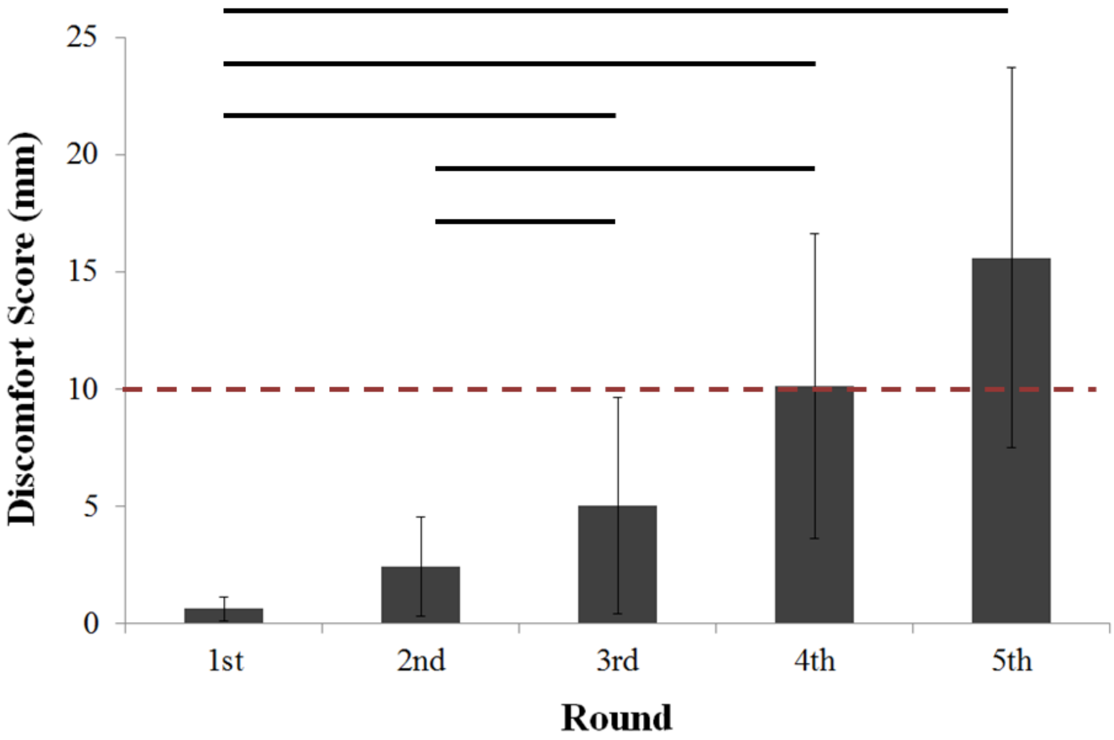

**Figure 5.7:** Mean (±SD) discomfort score increased during each round of the ECP to above clinical levels (dashed line at 10 mm) in the 4th and 5th round. Ends of horizontal bars indicate significant differences between rounds ($p<0.05$). For a detailed description of differences between rounds, refer to Table 5.8.

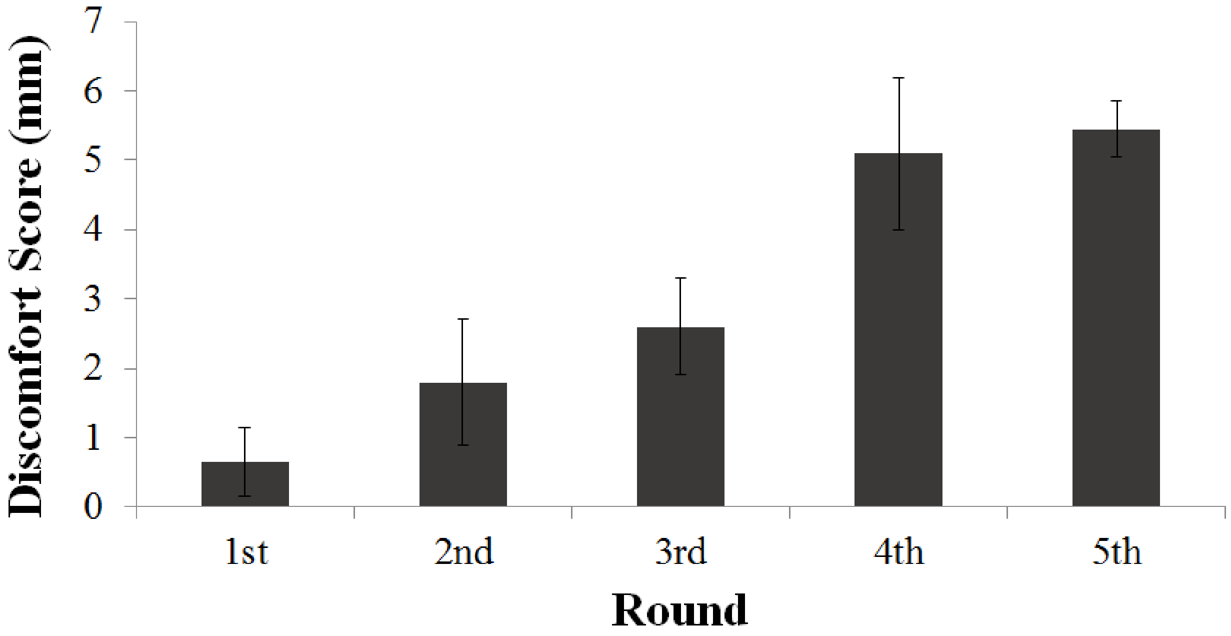

**Figure 5.8:** Relative discomfort scores showing the changes in discomfort score per round of the ECP. The increase in discomfort score begins from the start (1st round), and a significant increase in discomfort score is observed in the 4th and 5th round.

### *5.4 Heart Rate*

Heart rate monitoring is frequently used methods to assess physical activity (Ekeland et al., 2001). Participants' average resting heart rate was 62bpm. Reporting heart rate relative to resting heart rate allows adjustments for individual differences in age and fitness (Ekeland et al., 2001). Participants' heart rate exhibited a sharp increase early on and remained at a consistently high level throughout the remainder of the protocol (Figure 5.8). Significant differences were observed between all rounds ($F_{4,70}=23.21$, $p<0.001$). Heart rate ranged increased from 146 bpm ± 8.6 in the 1st round to 171bpm ± 4.5 in the 5th round.

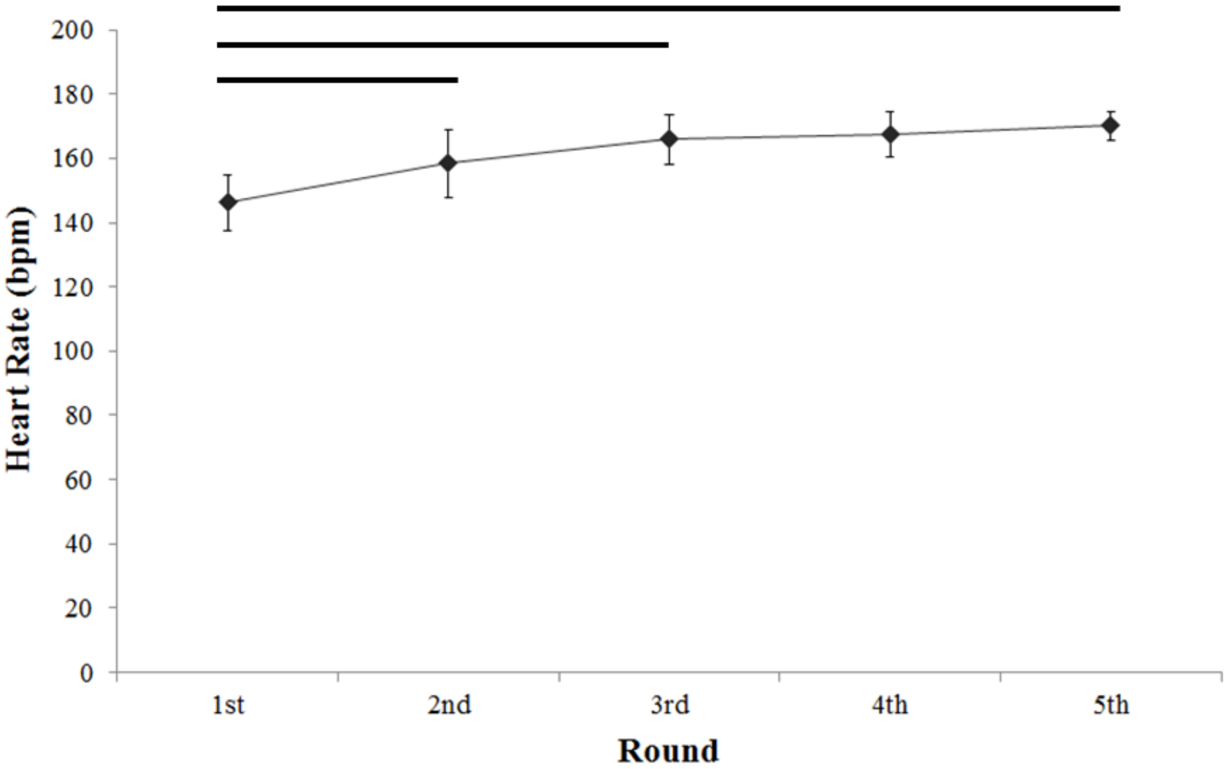

**Figure 5.9:** Mean (±SD) heart rate increased during each round of the ECP and is the highest at the 5th round. Ends of horizontal bars indicate significant differences between rounds ($p<0.05$). For significant differences between rounds, refer to Table 5.8.

Heart rate was also normalized as a % of maximum heart rate to account for influences of individual variabilities in sex, age, or fitness level (Ekeland et al., 2001) (Table 5.6). The intensity of physical activity is commonly defined in terms of percentages of maximum heart rate (Ekelund et al., 2001). No significant differences of heart rate (% maximum) were observed between all rounds ($F_{4,70}=0.94$, $p=0.45$). Although not significant, Table 5.6 shows that after completing the first round of the ECP, participants are at 76% ± 8.6 of maximum heart rate. As they progress through the workout, participants are working at a high intensity, as shown by a 90% ± 4.5 of maximum heart rate is reached by the last round (5th round).

**Table 5.6:** Comparison of mean (±SD) heart rate between rounds during the ECP. Heart rate was expressed as a % of maximum heart rate.

| **Round** | **1st** | **2nd** | **3rd** | **4th** | **5th** |
|---|---|---|---|---|---|
| Heart Rate (%) | 76.9 ± 8.6 | 83.4 ± 10.6 | 87.3 ± 7.7 | 88.1 ± 7.1 | 90 ± 4.5 |

**Table 5.7:** A pairwise comparisons of Tukeys *post-hoc* were used to establish whether any of the rounds for discomfort score and heart rate demonstrated significant differences from others. Shaded cells indicate a significant difference between rounds ($p<0.05$).

| | Rounds | *F*-Statistic |
|---|---|---|
| Discomfort Score | 1 to 2 | 0.06 |
| | 1 to 3 | <.0001 |
| | 1 to 4 | <.0001 |
| | 1 to 5 | <.0001 |
| | 2 to 3 | 0.009 |
| | 2 to 4 | 0.002 |
| | 2 to 5 | 0.003 |
| | 3 to 4 | 0.56 |
| | 3 to 5 | 0.22 |
| | 4 to 5 | 0.52 |
| Heart Rate (bpm) | 1 to 2 | <.0001 |
| | 1 to 3 | <.0001 |
| | 1 to 4 | <.0001 |
| | 1 to 5 | <.0001 |
| | 2 to 3 | 0.08 |
| | 2 to 4 | 0.06 |
| | 2 to 5 | 0.07 |
| | 3 to 4 | 0.55 |
| | 3 to 5 | 0.22 |
| | 4 to 5 | 0.51 |
| Heart Rate (%Max) | 1 to 2 | 0.08 |
| | 1 to 3 | 0.07 |
| | 1 to 4 | 0.14 |
| | 1 to 5 | 0.25 |
| | 2 to 3 | 0.23 |
| | 2 to 4 | 0.19 |
| | 2 to 5 | 0.06 |
| | 3 to 4 | 0.63 |
| | 3 to 5 | 0.57 |
| | 4 to 5 | 0.82 |

## 6. Discussion

ECP was shown to alter some movement patterns, muscle activation, and discomfort levels in experienced participants. Many studies have shown the potential health benefits of resistance training. These benefits include increase in musculoskeletal fitness (i.e. muscular strength, endurance and power), bone mineral density, functional capacity, metabolic rate, and increased quality of life (Carpinelli & Otto, 1998). However, recent studies on have shown that manual materials lifting is a documented risk factor of LBP (van Dieen et al., 1999). More specifically, the low back has been shown to be the area most often injured during ECP (Keogh and Winwood, 2017; Hak et al. (2013). As a result, many intervention strategies involve training and instruction with respect to lifting technique (Nygard et al., 1998).

### *6.1 Deadlift*

As the participants worked through the rounds, there was a significant change in postural angles in the trunk, hip, and knee across the 1st to the 5th rounds during the deadlift. Changes in kinematics included: increased spinal flexion in the UT and LT, decrease in hip angle, and a decrease in knee angle. These changes illustrate that participants were adopting a more straight legged, bent over posture, also referred to as a stooped posture. A study by Potvin et al. (1991) assessed muscular and ligament sources of extensor moment during dynamic lifting using various loads and flexion angles of the trunk. They assessed 15 participants lifting 30 reps at 5 different loads (5.8, 13.6, 21.5, 29.2, 32.4kg). Potvin et al. (1991) concluded that shear force was higher with a greater degree of lumbar flexion. As previously mentioned, the degree of lumbar flexion affects the line of action of the ES muscles and determines the ability of these muscles to resist damaging anterior shear forces on the spine (McGill, 2016). These results suggest that injury may be influenced more by the degree of flexion, rather than the choice of stoop or squat technique (Potvin et al., 1991). It is possible that the participants adopted greater flexion in the upper and lower thoracic regions in order to compensate for the change in hip angle. Also, the participants have a greater chance during the deadlift to increase spinal flexion as a result of external forces of the load being lifted combined with the weight of the upper body. Moreover, muscle activation in the TES and LES were higher in the deadlift than the squat exercise, which may be due to heavier loads being lifted in the deadlift exercise for all participants. Similar to previous literature, the RA EMG levels remained generally low, below 20% of maximum) during the lifts (Potvin et al., 1991). As the workout progressed, there was a decrease in mean muscle activity of the back muscles (TES, LES) across rounds 1 to 5. According to Crisco & Panjabi (1990), spinal muscles are responsible for stabilizing the spine to prevent buckling. Contracting muscles help to maintain a rigid spinal column, providing a strength advantage for the spinal musculature (Cholewicki & McGill, 1992). The decrease in muscle activity in round 5 could be a result of fatigue development from high exertion in the spinal musculature (Nygard et al., 1998), and the muscles activating in a bursting pattern to maintain force development. Development of fatigue is to be expected as participants completed majority of the protocol in the range of 70-90% max heart rate, which is defined by the ACSM as vigorous intensity. These findings are consistent with McGill et al. (2001), as the spine becomes increasingly flexed, load is transferred from active to passive tissues, due to the changes in muscle fiber orientation (McGill, 2016). The transfer of load, particularly shear, from active to passive tissue has been shown to be a major factor in increasing the risk of injury. Furthermore, in a study examining the deadlift, Cholewicki et al. (1991) evaluated reaction moments at the knee, hip, and L4/L5 joints in powerlifters competing in a national powerlifting championship. These authors noted that an increased forward spine angle at the bottom of the deadlift increases the risk of injury to the spine and back musculature. Although the deadlift is commonly performed to train the lower body and ES muscle groups and to develop power and strength (Camera et al., 2016), participants should be conscious of their posture to avoid the risk of developing LBP and injury. In addition to informing behaviour, having a knowledgeable trainer or coach to monitor posture during the performance of ECP exercises could also be beneficial in reducing the risk of injury.

### *6.2 Squat*

Compared to the deadlift, postural changes during the squat were not as prominent. Participants moved more towards a more erect spine posture while the hip and knee angles increased in flexion. While the deadlift exhibited increasing flexion at the spine, the squat exercise displayed the opposite effect. A study by Hooper et al. (2014) performed a similar protocol examining the changes in squat kinematics. These authors also found a decrease in knee angle and an increase in hip flexion as the protocol progressed. The present study differs from Hooper et al. (2014) by including participants with experience in ECP, whereas the previous authors did not have an inclusion criteria. Moreover, Hooper et al. (2014) recorded a 30° difference in hip angle between early and late protocol, compared to the present study where participants only showed 8°. A notable difference between the squat and deadlift exercise is the penalty for a partially completed repetition. If a participant begins a squat repetition and cannot complete it, they must drop the bar and then raise it to their shoulders in order to resume the next repetition. In contrast, if a participant begins the deadlift repetition and cannot complete it they can simply let go of the bar and let it drop to the ground. Therefore, aborting the squat exercise is much more energetically costly to the participant, and as a result it is likely that participants chose to rest longer during the squat exercise to ensure successful completion of the lift. As previously mentioned, the squat exercise showed less prominent changes in technique compared to the deadlift. Therefore, it is possible the results observed in this study were a result of the participants' experience level and training history may have had a positive effect in maintaining a more consistent technique and conservative completion of the squat component. Similar to the kinematics changes observed during the deadlift, a study by Cholewicki & McGill (1992) found that keeping a relatively rigid spinal column allowed the lifting movement to be accomplished mainly with extension of the knee and hip joints, while preserving the low back. However, implications of this study are limited to ECP and may not necessarily apply to other lifts, such as the industrial stoop, as well as lighter loads that are part of daily activity.

### *6.3 Discomfort*

Throughout the protocol, an increase in discomfort score was observed. At the 4th and 5th round, a change of greater than 10 mm was reported by participants, indicating the development of clinically significant levels in pain (Nelson-Wong & Callaghan, 2008). These results showed that discomfort scores increased with the increase in volume (number of sets completed). Previous literature has shown that low back discomfort during resistance training can be a result of muscular weakness (Graves et al., 1989). Due to the high intensity and minimal rest, participants did not always maintaining trunk motor control (likely due to fatigue), which increased their self-reported discomfort score. An adequate resistance training program is the most effective method for improving muscle strength, endurance of back and trunk muscles, and reducing self-reported pain (Ciolac & Rodrigues-da-Silva, 2016). Thus, a specific exercise that involves resistance training of the thoracic and lumbar muscles, such as the deadlift and the front squat, can help protect against developing low back pain (Graves et al., 1989).

## *6.4 Heart Rate*

The average heart rate exhibited a sharp increase early in the first two rounds of the workout and continued to rise gradually until the final round. Average heart rate in the 5th round reached 90% of normalized max HR, which is in the "vigorous exercise" or highest category for ACSM heart rate training zones (ACSM, 2015). As previously mentioned, heart rate has been shown to be an accurate predictor of exercise intensity (Strath et al., 2000). An increasing heart rate throughout the workout suggests participants are not taking adequate rest periods. The participants' flexibility to choose their own rest periods along with a desire to complete the workout as quickly as possible were factors that influenced their minimal rest time. However, it is also clear from these heart rate values that the participants' were able to maintain the desired high intensity and complete the ECP as directed.

## *6.5 Limitations*

As with any biomechanical research study of this nature, there are limitations that need to be considered. Participants in this study were tested while wearing large amounts of instrumentation. While the researchers consulted with participants to determine the optimal setup for comfort and ease of movement, it is possible that the instrumentation may have an effect on the manner in which the participants exercised. Also, Partridge et al. (2014) noted that a large motivational factor in CrossFit™ gyms was due to performance comparison with others. Despite participants being instructed to work out as they normally would, the fact that they were working out alone may have had an effect on participant’s motivation and intensity level. Lastly, exercises chosen in this study only demonstrate one type of ECP, whereas ECP often vary quite significantly. A major factor influencing variability between different ECP is exercise order. Previous literature has shown that exercise order should be determined based on movement patterns in greatest need of improvement (Simao et al., 2012). Exercise order affects repetition performance over multiple sets, indicating that the total repetitions (volume) is greater when an exercise is placed at the beginning of a resistance training session, regardless of relatively large or small muscle mass involved (Simao et al., 2012). Due to the use of participants outside of the university community, only one data collection session was possible, and so the effect of order could not be investigated.

## 7. General Thesis Overview

### *7.1 Hypotheses Revisited*

1. There would be statistically significant changes in kinematic measures of trunk and knee angles in both the deadlift and squat exercises across the 1st to the 5th rounds.

This hypothesis was **ACCEPTED**

Statistically significant changes were observed in spine, knee, and hip angles during both exercises with the largest changes being between rounds 1 and 5.

2. Activation of the hip and trunk musculature will increase significantly during both the squat and deadlift exercises across the 1st to the 5th rounds.

This hypothesis was **REJECTED**

Majority of muscles showed no changes in muscle activation throughout the protocol. The TES and LES muscles showed a decrease in muscle activation for both exercises, while RA activation was increased during the squat.

3. Heart rate would increase in response to the number of rounds completed. Heart rate will be positively associated with time.

This hypothesis was **REJECTED**

As participants progressed through the protocol, the initial increase steady rise in heart rate was observed to levels associated with maximal effort.

4. Experienced ECP participants would not report clinically significant discomfort scores (<10mm on VAS) during the workout.

This hypothesis was **ACCEPTED**

Average discomfort score was reported above clinically significant levels in the 4th and 5th round, indicating that participants experienced clinically relevant levels of low back pain.

## 8. Conclusion

This biomechanical evaluation of the deadlift and squat exercises has provided insight into understanding the safety of an ECP. When allowing participants to monitor their own rest periods and their technique, changes were observed in the kinematics, muscle activation, and discomfort levels as the participants progressed from the 1st round to the 5th round. With the changes observed in this study, participants choosing to engage in ECP should be aware of the greater risk of injury. Regardless of the magnitude of change, it is evident that during an ECP, participants are deviating from their original technique and these deviations become more pronounced with each successive round due to the increasing number of sets being completed. Along with these technique changes, changes in muscle activation and increases in back discomfort raise concern over the safety of ECP. It is interesting to note that all participants in the current study had been completing ECP regularly for at least 1 year, therefore participants less experienced than those in the current study would be expected to display even more prominent changes in technique (Hooper et al., 2014). These deviations in technique along with evidence that muscle, tendon and ligament adaptations take up to one year to respond to a new training stimulus (Brumitt & Cuddeford, 2015). These observations by Brumitt & Cuddeford (2015) raise particular concerns for those who are beginning an ECP. Future studies should evaluate even more experienced individuals as well as more inexperienced individuals, to understand the effects training level has in attenuating the changes observed in the kinematics and muscle activations (and so associated risk of injury). Lastly, future biomechanical studies should focus on how technique changes during an ECP when performed under the supervision of a qualified coach, as the current findings suggest a further reduction in risk of injury could be achieved by minimizing changes in kinematics.

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## Appendix A

**Table A1:** Summary of mean (±SD) muscle activation (%MVC) during the deadlift.

| **Round** | **1st** | **2nd** | **3rd** | **4th** | **5th** |
|---|---|---|---|---|---|
| RA | 8.8± 11.3 | 8.9± 11.8 | 8.6± 10.9 | 8.6± 12.1 | 14.6± 24.1 |
| EO | 8.7± 8.9 | 7.9± 7.4 | 7± 4.3 | 6.8± 4.2 | 9.5± 8.9 |
| IO | 14± 10.2 | 11.8± 7.7 | 10.9± 7.2 | 10.2± 7.4 | 13.1± 12.9 |
| TES | 29.3± 16.6 | 26.4± 12.8 | 24.3± 12.3 | 20.6± 11.3 | 25.3± 17.4 |
| LES | 32.4± 19.7 | 28.9± 17.2 | 25.2± 14.7 | 21.3± 14.3 | 23.1± 14.8 |
| BF | 18.2± 9.3 | 16.5± 6.8 | 14.8± 6.1 | 14.8± 6.8 | 16.5± 7.9 |
| RF | 21.5± 23.9 | 18.8± 16.3 | 17.2± 15.5 | 14.3± 15.4 | 19.3± 16.8 |
| GM | 22.3± 17.7 | 19.8± 15.7 | 17.9± 15.2 | 16± 13.4 | 21.4± 19.9 |

**Table A2:** Summary of mean (±SD) muscle activation (%MVC) during the squat.

| **Round** | **1st** | **2nd** | **3rd** | **4th** | **5th** |
|---|---|---|---|---|---|
| RA | 8.7± 10.4 | 10 ± 18.7 | 6.5± 3.8 | 12.3± 4.7 | 7.2± 4.4 |
| EO | 14.9± 9.5 | 15.6± 12 | 14.1± 8.5 | 12.6± 6.8 | 15.1± 13.5 |
| IO | 9.4± 9.3 | 10.6± 16.9 | 7.7± 3.9 | 10.9± 17.7 | 17.2± 29.4 |
| TES | 31 ± 17.1 | 31.5± 18.2 | 26.9± 15.2 | 25.2± 15.2 | 27.1± 18 |
| LES | 27.6± 14.1 | 25 ± 14.7 | 20.2± 11.9 | 19.6± 15.5 | 21.4± 16.8 |
| BF | 15.6± 11.4 | 16.4± 16.3 | 13.8± 8.4 | 15.6± 19 | 20.4± 26.7 |
| RF | 15.3± 17.5 | 14.4± 17.6 | 12.7± 14.8 | 11.1± 10.2 | 15.8± 19.4 |
| GM | 37.4± 22.3 | 34.6± 20.1 | 27.2± 19.2 | 31.5± 7.9 | 39.7± 62.5 |

**Table A3:** Summary of statistical analysis results of mean muscle activity (%MVC) during the deadlift and squat. The number of rounds were the main effect, with significant values ($p<0.05$) denoted by an asterisk (*).

| **Round** | **Deadlift Exercise** | **Squat Exercise** |
|---|---|---|
| | *F*-Statistic | *F*-Statistic |
| RA | **$F_{4,76}$=2.62, $p$=0.04*** | $F_{4,76}$=0.64, $p$=0.64 |
| IO | $F_{4,76}$=2.09, $p$=0.09 | $F_{4,76}$=1.13, $p$=0.35 |
| EO | $F_{4,76}$=1.54, $p$=0.19 | $F_{4,76}$=1.78, $p$=0.14 |
| BF | $F_{4,76}$=2.09, $p$=0.09 | $F_{4,76}$=0.04, $p$=0.99 |
| RF | $F_{4,76}$=1.89, $p$=0.12 | $F_{4,76}$=0.84, $p$=0.51 |
| GM | $F_{4,76}$=1.6, $p$=0.18 | $F_{4,76}$=0.95, $p$=0.44 |
| TES | **$F_{4,76}$=4.33, $p$=0.003*** | **$F_{4,76}$=2.99, $p$=0.02*** |
| LES | **$F_{4,76}$=4.86, $p$=0.002*** | **$F_{4,76}$=4.04, $p$=0.005*** |

**Table A4:** Summary of statistical analysis for muscle activity during the deadlift. No significant values were found for side and sex differences ($p<0.05$).

| **Deadlift Exercise** | **Side** | **Sex** |
|---|---|---|
| | *F*-Statistic | *F*-Statistic |
| RA | $F_{1,18}=3.34$, $p=0.08$ | $F_{1,18}=0.65$, $p=0.42$ |
| IO | $F_{1,18}=0.12$, $p=0.73$ | $F_{1,18}=0.52$, $p=0.48$ |
| EO | $F_{1,18}=2.21$, $p=0.15$ | $F_{1,18}=0.07$, $p=0.79$ |
| BF | $F_{1,18}=1.33$, $p=0.06$ | $F_{1,18}=0.65$, $p=0.42$ |
| RF | $F_{1,18}=1.63$, $p=0.21$ | $F_{1,18}=0.02$, $p=0.88$ |
| GM | $F_{1,18}=2.11$, $p=0.16$ | $F_{1,18}=0.88$, $p=0.36$ |
| TES | $F_{1,18}=0.18$, $p=0.67$ | $F_{1,18}=2.39$, $p=0.13$ |
| LES | $F_{1,18}=2.56$, $p=0.12$ | $F_{1,18}=0.01$, $p=0.98$ |

**Table A5:** Summary of statistical analysis for muscle activity during the squat. No significant values were found for side and sex differences ($p<0.05$).

| **Squat Exercise** | **Side** | **Sex** |
|---|---|---|
| | *F*-Statistic | *F*-Statistic |
| RA | $F_{1,18}=3.28$, $p=0.08$ | $F_{1,18}=0.35$, $p=0.56$ |
| IO | $F_{1,18}=0.82$, $p=0.37$ | $F_{1,18}=0.95$, $p=0.34$ |
| EO | $F_{1,18}=2.44$, $p=0.13$ | $F_{1,18}=0.36$, $p=0.83$ |
| BF | $F_{1,18}=1.7$, $p=0.44$ | $F_{1,18}=1.15$, $p=0.29$ |
| RF | $F_{1,18}=1.42$, $p=0.24$ | $F_{1,18}=0.15$, $p=0.71$ |
| GM | $F_{1,18}=0.2$, $p=0.66$ | $F_{1,18}=0.14$, $p=0.73$ |
| TES | $F_{1,18}=0.75$, $p=0.39$ | $F_{1,18}=0.07$, $p=0.79$ |
| LES | $F_{1,18}=0.19$, $p=0.66$ | $F_{1,18}=0.61$, $p=0.44$ |

**Table A6:** Comparison of mean (±SD) absolute flexion angles (°) between rounds during the deadlift exercise. Positive values indicate flexion.

| **Round** | **1st** | **2nd** | **3rd** | **4th** | **5th** |
|---|---|---|---|---|---|
| Head | 44.0 ± 14.4 | 48.5 ± 11.6 | 48.2 ± 15.6 | 49.3 ± 12.1 | 54.3 ± 7.6 |
| Left Shank | 15.1 ± 7.7 | 18.4 ± 8.8 | 14.6 ± 8.3 | 14.8 ± 9.6 | 14.8 ± 12.9 |
| Left Thigh | -51.9 ± 16.7 | -56.6 ± 12.7 | -53.9 ± 13.3 | -51.5 ± 16.9 | -53.4 ± 13.2 |
| Lower Thoracic | 74.9 ± 11.6 | 74.8 ± 10.9 | 75.6 ± 16.9 | 70.9 ± 30.4 | 76.9 ± 20.8 |
| Lumbar | 58.8 ± 18.1 | 64.3 ± 10.7 | 64.9 ± 13.4 | 64.3 ± 20.7 | 67.0 ± 9.7 |
| Neck | 44.1 ± 14.5 | 45.8 ± 11.8 | 50.3 ± 16.6 | 49.8 ± 12.4 | 53.9 ± 7.5 |
| Pelvis | 55.2 ± 20.9 | 57.3 ± 14.2 | 56.2 ± 17.6 | 54.0 ± 22.0 | 53.0 ± 17.4 |
| Right Shank | 16.1 ± 8.4 | 15.4 ± 9.9 | 14.2 ± 9.4 | 12.8 ± 9.6 | 16.2 ± 9.3 |
| Right Thigh | -53.4 ± 16.9 | -56.3 ± 12.7 | -52.8 ± 13.2 | -50.1 ± 14.4 | -51.8 ± 11.3 |
| Trunk | 68.3 ± 18.9 | 72.9 ± 11.4 | 72.1 ± 13.7 | 74.2 ± 19.5 | 78.0 ± 8.4 |
| Upper Thoracic | 60.8 ± 10.2 | 62.6 ± 11.4 | 63.4 ± 16.1 | 65.9 ± 18.9 | 69.1 ± 13.4 |

**Table A7:** Comparison of mean (±SD) absolute flexion angles (°) between rounds during the squat exercise. Positive values indicate flexion.

| **Round** | **1st** | **2nd** | **3rd** | **4th** | **5th** |
|---|---|---|---|---|---|
| Head | 10.5 ± 8.4 | 10.9 ± 8.6 | 11.7 ± 10.3 | 12.5 ± 11.4 | 13.6 ± 11.1 |
| Left Shank | 36.1 ± 8.8 | 36.2 ± 8.8 | 37.7 ± 8.7 | 37.6 ± 8.1 | 36.8 ± 9 |
| Left Thigh | -95.9 ± 10.6 | -97.7 ± 9.4 | -96.6 ± 8 | -97.1 ± 8.5 | -96 ± 8.3 |
| Lower Thoracic | 31.3 ± 9.7 | 30.5 ± 9.8 | 31.6 ± 6.5 | 30.7 ± 7.4 | 31.5 ± 7.3 |
| Lumbar | 23.9 ± 9.6 | 22.2 ± 10.3 | 22.6 ± 8.7 | 21.7 ± 9.3 | 21.9 ± 9.5 |
| Neck | 10.5 ± 8.4 | 10.9 ± 8.7 | 12.1 ± 10.1 | 12.5 ± 11.4 | 12.3 ± 8.7 |
| Pelvis | 20.1 ± 14.8 | 17.5 ± 17.2 | 17.5 ± 17.5 | 16.4 ± 16.9 | 16.6 ± 17.6 |
| Right Shank | 41 ± 13.3 | 41.1 ± 12 | 39.9 ± 10 | 39.7 ± 12.3 | 39.1 ± 10.5 |
| Right Thigh | -94 ± 12.2 | -93.8 ± 12 | -94 ± 9.1 | -91.7 ± 10.8 | -93.1 ± 11.5 |
| Trunk | 28.2 ± 8.7 | 28 ± 8.6 | 28.4 ± 8.1 | 27.9 ± 8.1 | 28.5 ± 8.3 |
| Upper Thoracic | 24.9 ± 9 | 25.8 ± 9.1 | 26.6 ± 7.6 | 27 ± 8.3 | 25.8 ± 8.4 |

**Table A8:** Summary of statistical analysis results of mean absolute angle measures (°) during the deadlift and squat. The number of rounds were the main effect, with significant values ($p<0.05$) denoted by an asterisk (*).

| Round | Deadlift Exercise<br>$F$-Statistic | Squat Exercise<br>$F$-Statistic |
|---|---|---|
| Head | $F_{4,76}=0.37, p=0.83$ | $F_{4,76}=0.45, p=0.77$ |
| Neck | $F_{4,76}=0.44, p=0.78$ | $F_{4,76}=0.44, p=0.77$ |
| Upper thoracic | $F_{4,76}=0.52, p=0.72$ | $F_{4,76}=2, p=0.1$ |
| Lower thoracic | $F_{4,76}=0.62, p=0.64$ | $F_{4,76}=0.93, p=0.45$ |
| Lumbar | $F_{4,76}=1.35, p=0.25$ | **$F_{4,76}=3.08, p=0.02*$** |
| Trunk | $F_{4,76}=1.25, p=0.29$ | $F_{4,76}=1.38, p=0.25$ |
| Pelvis | **$F_{4,76}=3.37, p=0.01*$** | $F_{4,76}=2.16, p=0.08$ |
| Right Thigh | **$F_{4,76}=4.76, p=0.002*$** | **$F_{4,76}=2.78, p=0.04*$** |
| Left Thigh | $F_{4,76}=2.31, p=0.06$ | **$F_{4,76}=3.96, p=0.007*$** |
| Right Shank | **$F_{4,76}=4.33, p=0.004*$** | $F_{4,76}=0.23, p=0.92$ |
| Left Shank | **$F_{4,76}=2.92, p=0.03*$** | $F_{4,76}=2.26, p=0.07$ |

**Table A9:** Summary of statistical analysis for absolute flexion angles during the deadlift and squat. No significant values were found for sex differences ($p<0.05$).

| | Deadlift Exercise<br>*Sex* $F$-Statistic | Squat Exercise<br>*Sex* $F$-Statistic |
|---|---|---|
| Head | $F_{1,18}=0.3, p=0.85$ | $F_{1,18}=3.17, p=0.09$ |
| Neck | $F_{1,18}=0.43, p=0.78$ | $F_{1,18}=2.69, p=0.11$ |
| Upper thoracic | $F_{1,18}=1.14, p=0.29$ | $F_{1,18}=0.02, p=0.87$ |
| Lower thoracic | $F_{1,18}=0.15, p=0.7$ | $F_{1,18}=0.3, p=0.59$ |
| Lumbar | $F_{1,18}=0.02, p=0.88$ | $F_{1,18}=0.33, p=0.57$ |
| Trunk | $F_{1,18}=0.09, p=0.76$ | $F_{1,18}=0.06, p=0.81$ |
| Pelvis | $F_{1,18}=0.35, p=0.56$ | $F_{1,18}=1.51, p=0.23$ |
| Right Thigh | $F_{1,18}=2, p=0.17$ | $F_{1,18}=0.86, p=0.36$ |
| Left Thigh | $F_{1,18}=0.09, p=0.77$ | $F_{1,18}=0.34, p=0.56$ |
| Right Shank | $F_{1,18}=2.22, p=0.15$ | $F_{1,18}=0.03, p=0.91$ |
| Left Shank | $F_{1,18}=1.42, p=0.24$ | $F_{1,18}=0.46, p=0.51$ |

**Table A10:** Comparison of mean (±SD) of flexion angles (% maximum flexion) between rounds during the deadlift exercise. Absolute flexion angles were normalized to maximum flexion.

| **Round** | **1st** | **2nd** | **3rd** | **4th** | **5th** |
|---|---|---|---|---|---|
| Upper Thoracic | 44.5± 3.8 | 44.2± 3.7 | 45.4± 3.5 | 46± 6.2 | 51.2± 1.4 |
| Lower Thoracic | 63± 6.4 | 63.7± 8 | 65.6± 8.3 | 65± 9.6 | 67.2± 8.6 |
| Lumbar | 64.8± 2.4 | 66.1± 2.4 | 68.7± 2.2 | 70.8± 1.6 | 72.4± 2.9 |
| Trunk | 64.1± 2.9 | 65.2± 3.2 | 67.4± 1.7 | 67.1± 3 | 68.8± 3.8 |

**Table A11:** Comparison of mean (±SD) of flexion angles (% maximum flexion) between rounds during the squat exercise. Absolute flexion angles were normalized to maximum flexion.

| **Round** | **1st** | **2nd** | **3rd** | **4th** | **5th** |
|---|---|---|---|---|---|
| Upper Thoracic | 18± 1.4 | 18.3± 1.1 | 17± 1.6 | 16.9± 1.1 | 17.1± 1.7 |
| Lower Thoracic | 28.5± 1 | 27.2± 0.8 | 26.1± 1.1 | 25.4± 1.2 | 25.4± 1.1 |
| Lumbar | 28.7± 0.8 | 26.6± 1.4 | 24.7± 0.6 | 24.3± 1.8 | 21.5± 1.2 |
| Trunk | 26.8± 1.1 | 26.1± 1.2 | 25.5± 1.4 | 25.4± 1.3 | 23.3± 1.5 |

**Table A12:** Summary of statistical analysis results for mean trunk angle measures (°) (expressed as a % of maximum flexion) during the deadlift and squat. The number of rounds were the main effect, with significant values ($p<0.05$) denoted by an asterisk (*).

| **%ROM** | **Deadlift Exercise**<br>*F*-Statistic | **Squat Exercise**<br>*F*-Statistic |
|---|---|---|
| Upper Thoracic | **$F_{4,66}=3.64$, $p=0.009*$** | **$F_{4,66}=2.61$, $p=0.04*$** |
| Lower Thoracic | **$F_{4,66}=3.07$, $p=0.02*$** | **$F_{4,66}=7.33$, $p<0.001*$** |
| Lumbar | $F_{4,66}=1.57$, $p=0.19$ | **$F_{4,66}=17.04$, $p<0.001*$** |
| Trunk | $F_{4,66}=1.35$, $p=0.26$ | **$F_{4,66}=3.7$, $p=0.008*$** |

**Table A13:** Comparison of mean (±SD) relative flexion angles (°) between rounds during the deadlift exercise. Positive values indicate flexion.

| **Round** | **1st** | **2nd** | **3rd** | **4th** | **5th** |
|---|---|---|---|---|---|
| C7 | -13.2 ± 7.2 | -12.7 ± 9.3 | -13.5 ± 8.2 | -12.2 ± 12.2 | -9.8 ± 8 |
| T6 | -11.2 ± 3.2 | -10.7 ± 4.5 | -9.6 ± 4.8 | -9 ± 6.1 | -6.1 ± 6.3 |
| T12 | 11.6 ± 7.7 | 12.3 ± 7.9 | 14.7 ± 8.1 | 12.9 ± 10.1 | 15.6 ± 9 |
| S2 | 6.2 ± 13.7 | 6.9 ± 12.8 | 9 ± 12.6 | 11.9 ± 10.7 | 10.1 ± 13.4 |
| Left Hip | 112.5 ± 14.9 | 112.2 ± 14.2 | 111.8 ± 14.3 | 108.8 ± 19.5 | 102.7 ± 14.3 |
| Left Knee | 73 ± 18.7 | 79.8 ± 18.5 | 72.3 ± 17.2 | 68.6 ± 22.1 | 68.5 ± 20 |
| Right Hip | 112.9 ± 14.4 | 113.9 ± 14.7 | 112.5 ± 13.3 | 108 ± 17.4 | 108.8 ± 18.5 |
| Right Knee | 75.6 ± 17.2 | 76.1 ± 21.7 | 70.3 ± 21.2 | 68.2 ± 19.6 | 71.5 ± 20 |

**Table A14:** Comparison of mean (±SD) relative flexion angles (°) between rounds during the squat exercise. Positive values indicate flexion.

| **Round** | **1st** | **2nd** | **3rd** | **4th** | **5th** |
|---|---|---|---|---|---|
| C7 | -11.6 ± 17.9 | -11.6 ± 17.1 | -10.9 ± 17.5 | -11.1 ± 17.5 | -10.4 ± 19.1 |
| T6 | 112.9 ± 14.8 | 111.6 ± 16.3 | 108.5 ± 17.2 | 109.3 ± 17.9 | 105.3 ± 17.4 |
| T12 | 127 ± 14.2 | 125.4 ± 13.5 | 128.2 ± 12.1 | 131.2 ± 11.4 | 129.8 ± 13.7 |
| S2 | 109.4 ± 12.5 | 110.2 ± 17.1 | 108.5 ± 16.9 | 107.5 ± 19.6 | 104.8 ± 16.0 |
| Left Hip | 7.1 ± 9.6 | 9.3 ± 10.2 | 8.7 ± 9.9 | 8.8 ± 11.5 | 9.5 ± 10.9 |
| Left Knee | 4.7 ± 11.6 | 5.6 ± 13.9 | 5.8 ± 14.9 | 5.7 ± 12.4 | 6.2 ± 14.4 |
| Right Hip | 7.9 ± 7.5 | 8.9 ± 7.5 | 8.6 ± 7 | 9.2 ± 7.0 | 9.7 ± 7.3 |
| Right Knee | 7.1 ± 4.0 | 5.3 ± 4.3 | 5 ± 4.2 | 4.7 ± 5.0 | 5.1 ± 5.4 |

**Table A15:** Summary of statistical analysis results for mean relative angle measures (°) during the deadlift and squat. The number of rounds were the main effect, with significant values ($p$<0.05) denoted by an asterisk (*).

| **Round** | **Deadlift Exercise**<br>*F*-Statistic | **Squat Exercise**<br>*F*-Statistic |
|---|---|---|
| $C_7$ | **$F_{4,76}$=2.58, $p$=0.04*** | **$F_{4,76}$=2.87, $p$=0.03*** |
| $T_6$ | $F_{4,76}$=1.91, $p$=0.12 | **$F_{4,76}$=5.48, $p$=0.001*** |
| $T_{12}$ | **$F_{4,76}$=2.91, $p$=0.03*** | **$F_{4,76}$=6.65, $p$=0.001*** |
| $S_2$ | **$F_{4,76}$=2.83, $p$=0.03*** | $F_{4,76}$=0.74, $p$=0.57 |
| Left Hip | **$F_{4,76}$=6.51, $p$=0.001*** | **$F_{4,76}$=3.92, $p$=0.007*** |
| Right Hip | **$F_{4,76}$=2.81, $p$=0.03*** | **$F_{4,76}$=2.81, $p$=0.03*** |
| Left Knee | $F_{4,76}$=1.6, $p$=0.17 | **$F_{4,76}$=3.7, $p$=0.01*** |
| Right Knee | $F_{4,76}$=1.96, $p$=0.11 | $F_{4,76}$=0.24, $p$=0.91 |

**Table A16:** Summary of statistical analysis for relative flexion angles during the deadlift and squat. No significant values were found for sex differences ($p$<0.05).

| | **Deadlift Exercise**<br>*Sex F*-Statistic | **Squat Exercise**<br>*Sex F*-Statistic |
|---|---|---|
| $C_7$ | $F_{1,18}$=1.05, $p$=0.38 | $F_{1,18}$=0.09, $p$=0.77 |
| $T_6$ | $F_{1,18}$=0.1, $p$=0.75 | $F_{1,18}$=0.16, $p$=0.69 |
| $T_{12}$ | $F_{1,18}$=0.12, $p$=0.73 | $F_{1,18}$=1.65, $p$=0.17 |
| $S_2$ | $F_{1,18}$=0.3, $p$=0.58 | $F_{1,18}$=1.12, $p$=0.31 |
| Left Hip | $F_{1,18}$=0.01, $p$=0.93 | $F_{1,18}$=0.16, $p$=0.69 |
| Right Hip | $F_{1,18}$=0.16, $p$=0.69 | $F_{1,18}$=0.65, $p$=0.43 |
| Left Knee | $F_{1,18}$=0.6, $p$=0.45 | $F_{1,18}$=1.7, $p$=0.21 |
| Right Knee | $F_{1,18}$=2.05, $p$=0.16 | $F_{1,18}$=3.4, $p$=0.82 |

**Table A17:** Summary of statistical analysis results for discomfort score (mm) and heart rate (bpm). The number of rounds were the main effect, with significant values ($p$<0.05) denoted by an asterisk (*).

| **Effect** | **Round**<br>*F*-Statistic |
|---|---|
| Discomfort Score | **$F_{4,95}$=13.57, $p$<0.001*** |
| Heart Rate | **$F_{4,70}$=23.21, $p$<0.001*** |

**Table A18:** Comparison of mean (±SD) lateral bend angles (°) between rounds during the deadlift exercise. Positive values indicate lateral bend to the right.

| **Round** | **1st** | **2nd** | **3rd** | **4th** | **5th** |
|---|---|---|---|---|---|
| Head | 1.1 ± 1.6 | 1.1 ± 2.5 | 1.3 ± 1.8 | -1.6 ± 7.6 | -2.6 ± 8.6 |
| Neck | 0.1 ± 1.7 | 0.4 ± 2.1 | 0.5 ± 1.9 | -1.3 ± 4.5 | -1.6 ± 5.7 |
| Upper thoracic | -1.4 ± 2.6 | -1 ± 2.6 | -0.9 ± 4.1 | -1.2 ± 3.3 | 0.7 ± 3 |
| Lower thoracic | -0.6 ± 2.6 | 0.1 ± 2.6 | -0.3 ± 4.2 | 0.4 ± 3 | 1.2 ± 1.6 |
| Lumbar | -0.1 ± 2.5 | 1.4 ± 2.9 | 0.7 ± 3 | 1.5 ± 3.6 | 0.2 ± 2.7 |
| Trunk | -1.9 ± 4.6 | -1.3 ± 5.2 | -1.2 ± 4.7 | 0.1 ± 2.5 | -0.1 ± 2.5 |
| Pelvis | -2.1 ± 5.2 | -1.8 ± 4.5 | -1.7 ± 4.9 | -1.1 ± 4.8 | -1.5 ± 4 |
| Right Thigh | 0.1 ± 1.7 | 0.4 ± 2.1 | 0.5 ± 1.9 | 0.5 ±1.7 | 0.9±1.4 |
| Left Thigh | -0.4 ± 2.6 | -0.2 ± 3.6 | -0.5 ± 3.1 | 0.6 ±2.6 | 0.1 ±3.6 |
| Right Shank | 0.1 ± 2.6 | 0.2 ± 4.2 | 0.4 ± 3 | 0.1 ± 1.6 | -0.7 ±3.7 |
| Left Shank | 0.3 ± 2.6 | 0.1 ± 4.2 | 0.2 ± 3 | -0.1 ±2.6 | -0.9 ±2.7 |

**Table A19:** Comparison of mean (±SD) axial twist angles (°) between rounds during the deadlift exercise. Positive values indicate axial twist to the right.

| **Round** | **1st** | **2nd** | **3rd** | **4th** | **5th** |
|---|---|---|---|---|---|
| Head | -0.2 ±0.8 | -0.1 ±0.9 | -0.8 ±0.7 | -0.6 ± 0.6 | -0.6 ± 0.6 |
| Neck | -1.3 ±0.9 | -1 ±0.9 | -1.7 ±1.5 | -2.6 ±1.3 | -1.2 ±0.2 |
| Upper thoracic | -2.9 ±5.1 | -4 ±8.4 | -1.7 ±8.2 | 1.2 ± 2.3 | 0.7 ± 3 |
| Lower thoracic | -0.9 ±7.5 | -3.6 ±8.5 | -0.7 ±7.8 | 0.4 ± 3 | 1.2 ± 1.6 |
| Lumbar | -3.9 ±7.0 | 1.4 ± 1.9 | -1.3 ±2.9 | 3.5 ± 3.6 | 2.2 ± 2.7 |
| Trunk | -3.4 ±6.8 | -1.3 ± 5.2 | -2.2 ±6.0 | 0.1 ± 2.5 | -0.1 ± 2.5 |
| Pelvis | -3.9 ±7.0 | -1.8 ± 4.5 | -3.7 ±6.5 | -1.1 ± 4.8 | -1.5 ± 4 |
| Right Thigh | -0.4 ±7.8 | 0.4 ± 2.1 | -3.7 ±7.0 | 0.5 ±1.7 | 0.9±1.4 |
| Left Thigh | -3 ±8.5 | -2.6 ±7.3 | -1.2 ±6.2 | -4.9 ±5.2 | -1.5 ±3.4 |
| Right Shank | -2.7 ±7.9 | -3.7 ±6.5 | -4 ±8.4 | -3 ±8.5 | -4.2 ±7.8 |
| Left Shank | -2 ±7.9 | -2.3 ±7.6 | -2.8 ±7.3 | -3 ±7.0 | -3.4 ±6.8 |

**Table A20:** Comparison of mean (±SD) lateral bend angles (°) between rounds during the squat exercise. Positive values indicate lateral bend to the right.

| **Round** | **1st** | **2nd** | **3rd** | **4th** | **5th** |
|---|---|---|---|---|---|
| $C_7$ | 0.2 ±1.2 | -0.7 ±3.7 | 0.1 ±1.4 | 0.5 ± 1.0 | 0.6 ± 2.5 |
| $T_6$ | 0.9±1.4 | 0.1 ± 1.6 | -0.3 ± 1.6 | 0.5 ±2.0 | 0.3 ± 1.6 |
| $T_{12}$ | 0.6 ±2.6 | 0.1 ±3.6 | -0.3 ±2.1 | -0.2 ±1.2 | 0.6 ±2.6 |
| $S_2$ | 1.1 ±1.3 | 0.3 ±1.7 | 1.1 ±4.5 | -0.7 ± 2.9 | 1.3 ± 3.5 |
| Left Hip | -0.9 ±2.7 | 0.4 ±3.1 | -0.3 ±3.2 | -0.6 ±2.6 | 2.2 ± 2.7 |
| Right Hip | -0.3 ± 1.6 | 0.7 ±2.1 | 0.3 ±1.3 | -0.2 ±1.9 | -0.1 ± 2.5 |
| Left Knee | -0.8 ±3.2 | 0.6 ±2.6 | 0.1 ±3.6 | 0.3 ± 2.6 | -0.5 ± 2.8 |
| Right Knee | 0.4 ±2.6 | 1.5 ±3.6 | 0.5 ±3.7 | -1.1 ±2.5 | 0.9 ± 3.9 |

**Table A21:** Comparison of mean (±SD) axial twist angles (°) between rounds during the squat exercise. Positive values indicate axial twist to the right.

| **Round** | **1st** | **2nd** | **3rd** | **4th** | **5th** |
|---|---|---|---|---|---|
| $C_7$ | -1.2 ±1.3 | -1.7 ±1.8 | 6.4 ±3.3 | 4.9 ±2.6 | -0.7 ±3.7 |
| $T_6$ | -0.8 ±1.7 | 0.3 ±2.3 | -0.4 ±1.1 | -0.1 ±2.4 | -0.5 ±3.1 |
| $T_{12}$ | 0.2 ±2.3 | -0.4 ±2.6 | -0.2 ±1.4 | -0.3 ±1.7 | 1.2 ±1.9 |
| $S_2$ | 1.6 ±2.3 | 0.9 ±1.8 | 1.6 ±1.5 | 1.5 ±1.7 | 1.3 ± 4.5 |
| Left Hip | -1.1 ±5.9 | 6.8 ±4.5 | -5.5 ±2.8 | 7.1 ±5.9 | -4.2 ± 2.7 |
| Right Hip | -1.3 ±1.5 | 7.1 ±7.7 | -5.7 ±5.7 | 7.9 ±3.4 | -4.1 ± 2.5 |
| Left Knee | -0.7 ±2.4 | -0.8 ±2.1 | -0.5 ±2.4 | -0.3 ± 2.6 | -1.6 ±2.2 |
| Right Knee | 0.8 ±4.6 | 1.5 ±4.8 | 0.5 ±3.7 | 1.1 ±4.5 | 0.9 ±1.8 |

**Appendix B**

## Pre-Test Questionnaire

The following questionnaire is voluntary and we only ask that you answer the questions to the best of your ability. If for any reason you do not feel comfortable answering any or some of the questions, you may leave them blank. Leaving answers blank is acceptable and there are no penalties for doing so.

**Date: ___________________________** **Participant code: ______________________**

**Height: _______ (m)**
**Weight:_______ (kg)**

1. **Do you perform the squat and deadlift as part of your regular routine? Yes / No**
2. **If answered Yes to #1, please indicate how many times a week you squat and deadlift (combined total)**

   **_______ times per week** **_______ hours/week**
3. **What is the number of hours a week you lift weights: _______ hours/week**
4. **How many years have you been lifting weights? ____ years**
5. **Do you currently perform extreme conditioning protocols (CrossFit™, Gym Jones etc.) as part of your regular routine? Yes / No**
6. **How long have you been participating in extreme conditioning protocols? __________________**
7. **Front Squat 1RM: ___________________**
8. **Deadlift 1RM: ______________________**
9. **Have you ever been coached/taught by a fitness professional on how to perform squats and deadlifts? Yes / No**
10. **Do you or have you every competed professionally in a sport or event? Yes / No**

11. **Have you ever had low back pain? Yes / No**

12. **If you answered Yes to question #11, please indicate if you have had low back pain in the last 12 months? Yes / No**

13. **If you answered yes to question #10, has your low back pain caused you to miss training or work? Yes / No**

14. **If you answered yes to question #10, please indicate how long you had missed training or work for? ________days**

15. **If you answered yes to question #10, have you ever seen a health care professional (i.e. medical doctor, chiropractor, physiotherapist, etc.) about your low back pain? Yes / No**

16. **Do you regularly experience pain anywhere else? (Please circle one) Yes / No**

17. **If you answered yes to question #16, where do you experience this pain?**

    ________________________________________________________________________________

18. **Have you had any serious injuries within the past 12 months??? If so, explain.**

    ________________________________________________________________________________

19. **Do you have any other comments you wish to make to the research group at this time?**

    ________________________________________________________________________________

    ________________________________________________________________________________

    ________________________________________________________________________________

    ________________________________________________________________________________

Thank you for your time! Please return the questionnaire to Steve.