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The Influence of Hip Mobility and Fatigue on Spinal Flexion and Muscle Activation in Rugby Scrum Performance

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Abstract

Introduction: Rugby scrumming is a means of restarting play following a minor rule infringement that can occur up to 28 times per game. The scrum poses a significant injury risk, with more days missed due to injury per event than any other rugby activity. Rugby players also have a significantly higher rate of spine injury than the general population, perhaps due to flexion in combination with high compression forces, which has been cited as the main mechanism of injury. Flexion of the spine has also been associated with poor hip mobility and quadriceps fatigue in other athletic tasks and may influence rugby scrumming similarly. Therefore, the purpose of this study was to determine if spine flexion, force output and muscle activation are influenced by 1) fatigue and 2) hip mobility in individual machine rugby scrumming.

Methods: Sixteen participants with at least 4 years of rugby scrumming experience were recruited to complete the study. In the initial scrumming block, the participants completed five 5-second scrumming trials with 1-2 minutes rest in between each trial. They then performed a wall sit to fatigue and performed five more 5-second scrumming trials, this time with only 5 seconds of recovery in between each trial. The angle of each spinal region (Lumbar, Thoracic, Cervical), the muscle activation (quadriceps, lumbar and thoracic erector spinae and abdominal muscles) and the force output were all measured throughout each trial. A one-way repeated measures ANOVA was conducted (the factor being pre or post wall sit fatigue) to determine the influence of wall sit fatigue. A related samples t-test was conducted between the first and fifth trial of each block to determine the effect of repetitive scrumming, and correlations were conducted between different measures of hip mobility and the main output measures to determine the relationship with hip mobility.

Results: Wall sit fatigue led to a decrease in Thoracic Erector Spinae (left: $p = 0.0003$, right: $p < 0.0001$) and External Oblique (left: $p = 0.0009$, right: $p < 0.0001$) activation and an increase in average ($p < 0.0001$) and max ($p < 0.0001$) cervical flexion during the contact phase (contact with the scrum machine shoulder pads).

Prior to the wall sit, repetitive scrumming led to a decrease in activation of the Thoracic Erector Spinae (left: $p = 0.0109$, right: $p = 0.0005$) and left quadriceps (VM: $p = 0.0271$, VL: $p = 0.0473$) during the contact phase.

Following the wall sit, repetitive scrumming led to a decrease in Thoracic Erector Spinae Activation (left: $p = 0.0462$, right: $p = 0.0095$), and an increase in quadriceps activation (left: VM: $p = 0.0367$, VL: $p = 0.0419$; right: VM: $p = 0.0238$, VL: $p = 0.0213$). Further, repetitive scrumming led to an increase in thoracic average ($p = 0.0224$) and maximum ($p = 0.0058$) flexion angle and an increase in cervical average ($p = 0.0142$) and maximum ($p = 0.0048$) flexion angle. It also led to an increase in Lumbar spine angle deviation ($p = 0.0088$) and force output deviation ($p = 0.0404$).

Increased hip flexion range of motion was moderately related to increased impact peak force output ($r = 0.55$; $p = 0.0290$). Increased wall sit time was moderately related to increased impact peak ($r = 0.52$; $p = 0.0376$) and sustained push force ($r = 0.54$; $p = 0.0376$) for the trial prior to the wall sit.

Discussion and Conclusion: It appears that fatigue, whether induced by the wall sit or by repetitive scrumming, tends to lead to a decrease in activation of the Thoracic Erector Spinae and an increase in cervical flexion. This may be due to a variety of mechanisms: a greater extension of the lower limb leading to more compensatory flexion up the kinetic chain, direct fatigue of the Thoracic Erector Spinae, central fatigue acting on the Thoracic Erector Spinae, decreased co-contraction of the trunk as a result of fatigue, and/or disuse of the cervical region during machine scrumming. This relationship needs to be explored using more rugby specific fatigue protocols, as well as in live scrumming. Surprisingly, force output was influenced very little by fatigue, indicating that the individuals were able to use compensatory mechanisms to mitigate fatigue. There also existed very little relationship between hip mobility and spine angle, likely attributable to the lack of hip range of motion used during scrumming. There did appear to be a relationship between hip flexion range of motion and impact force, which may be attributable to a greater available distance of hip acceleration with greater hip mobility, leading to a greater impact. Wall sit time was also positively related to impact peak and sustained push which may indicate a benefit to using this test as a predictive measure to determine force output capacity in an isometric movement such as the rugby scrum.

Acknowledgements

I would like to start by acknowledging my supervisor Dr. Diane Gregory. I say with absolute certainty that this project could have never happened without your willingness and openness to try something new and for that I am extremely grateful. Thank you for being a very present supervisor while simultaneously balancing your own children, often in a literal sense. There were many odd requests that went along with completing this project and I thank you for making sure that all I needed was more than accounted for.

I would also like to thank my lab mates and friends in the master's program. This thesis has been a different format of learning than I have ever experienced and I appreciate those who have been there along the way to make sense of it all. I value the late night memories, funny stories, friends and roommates I have gained over the past two years. I would like to give a special thank you to my lab mates for volunteering their time and effort in order to help me with my thesis, and for taking an interest in it.

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I would like to extend a sincere thank you to my participants, whose flexibility and attitude made it a pleasure to conduct this research. I would also like to thank them for their effort, particularly in the wall sit, as they suffered in the name of science.

Last, I would like to thank my family. All of the conversations around the dinner table, spontaneous debates, and taking turns playing devil's advocate were an important ingredient in the curiosity I've developed that has carried me through my postsecondary education. Thank you for being a constant source of support and for always challenging me in ways that have shaped the person and student I am today. And most of all, through all the moving and changing through the last few years, thanks for letting me know there is always a place I can call home.

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List of Abbreviations:

ANOVA – Analysis of variance

EMG – Electromyography

ES – Erector Spinae

EO – External Oblique

FFT – Fast Fourier transform

ICC – Interclass correlation coefficient

IVD - Intervertebral disc

LES – Lumbar Erector Spinae

MdPF – Median power frequency

MVC –Maximum voluntary contractions

RA – Rectus Abdominis

ROM – Range of motion

SD – Standard Deviation

TES – Thoracic Erector Spinae

VL – Vastus Lateralis

VM – Vastus Medialis

1. Introduction

Rugby is a sport with frequent physical contact, characterized by a high degree of injury relative to most other team sports (Trewartha, Preatoni, England, & Stokes, 2014). Rugby is dynamic in nature and consists primarily of bouts of maximal sport-specific activity such as the ruck, scrum, tackle and maul, followed by submaximal recovery (Deutsch, Kearney, & Rehrer, 2007; Roberts, Stokes, Weston, & Trewartha, 2010). The scrum is a means of restarting play following a minor rule infringement whereby eight players from each team exert force on one another in order to win possession of the ball (Quarrie & Wilson, 2000; Trewartha et al., 2014). Only those positioned as forwards participate in the scrum, and they act together as a unit of eight known as the “pack” (Figure 1).

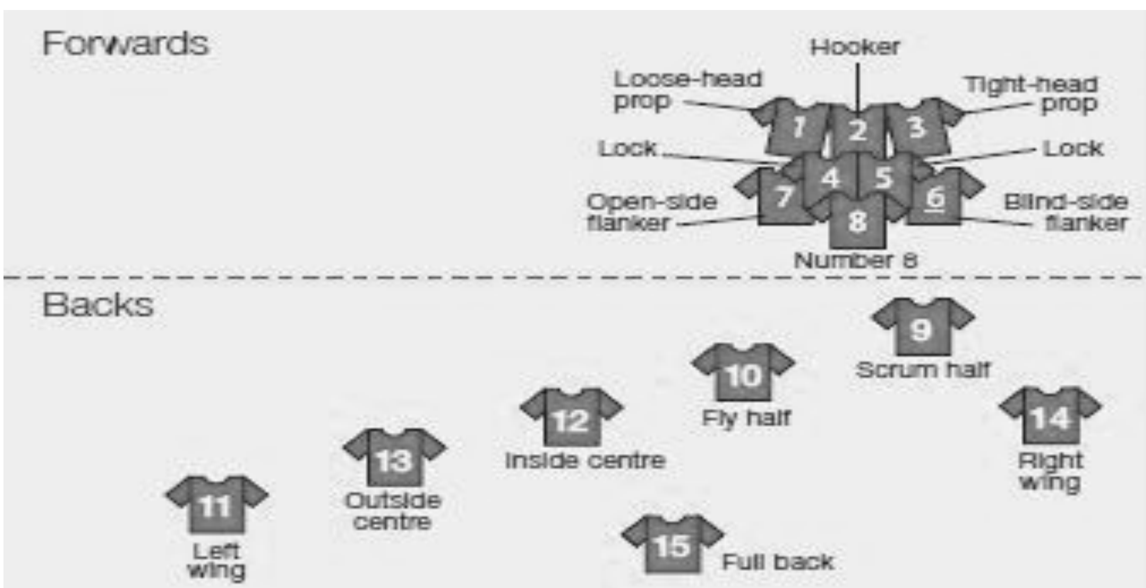

Figure 1: The positions of rugby. Only the forwards (numbers 1-8) are involved in pushing the scrum and are known as "the pack". Retrieved from http://tigersrugby.com/positions-in-rugby/

The scrum is an important part of the game given that it can act as an integral component of determining psychological and physical supremacy over the other team (Quarrie & Wilson, 2000). Success in the scrum can also yield a significant advantage in the score given that the scrum is a relatively frequent event in a rugby match, occurring approximately 28 times a game in professional English rugby (Fuller, Brooks, Cancea, Hall, & Kemp, 2007). Though the scrum is an important component of a rugby match, it also poses a significant health risk to the athletes, with more missed days due to injury per event than the tackle, ruck, maul or any other rugby activity (Brooks, Fuller, Kemp, & Reddin, 2005; Fuller et al., 2007). This may be the result of the high forces experienced by players (Preatoni, Stokes, England, & Trewartha, 2013; Trewartha et al., 2014) in combination with flexion of the spine (Quarrie, Cantu, & Chalmers, 2002; Wade, Robertson, Thambyah, & Broom, 2014) which has been cited as the most common mechanism of scrum injury (Quarrie et al., 2002).

While there have been studies looking at risk factors, such as anthropometrics including BMI and mass, that predispose individuals to being injured in the scrum (Quarrie et al., 2002; Trewartha et al., 2014) and rule changes have attempted to reduce the number of injuries in the scrum (Bohu et al., 2009; Cazzola, Stone, Holsgrove, Trewartha, & Preatoni, 2015; Cazzola, Preatoni, Stokes, England, & Trewartha, 2014), there has been very little research into the role of joint mobility and fatigue and its effect on scrum injuries. More specifically, reduced sagittal mobility of the hips has been linked to increased spinal flexion in lifting postures (Dolan & Adams, 1993) and sitting (Kang, Oh, Park, & Kim, 2013) and quadriceps fatigue has been associated with increased spinal flexion in firefighting (Gregory, Narula, Howarth, Russell, & Callaghan, 2008) and in lifting tasks (Trafimow, Schipplein, Novak, & Andersson, 1993). Given the similarity between scrumming and lifting postures involving flexion and extension of the lower joint in a constrained kinetic chain system, a deficit in a joint such as the hip or fatigue in the quadriceps may therefore affect scrumming posture in a similar fashion that it affects lifting (increased spinal flexion).

Given that previous work has found a relationship between spinal flexion and both quadriceps fatigue and hip mobility, the purpose of this study was to examine a fatiguing protocol of the knee extensors during a simulated individual rugby scrum in order to determine the influence of muscular fatigue on spinal posture, muscle activation and force output. Further, the correlation of hip mobility to spinal flexion and force output was conducted to determine the effect of sagittal hip mobility on the rugby scrum. Lastly, anthropometrics and performance measures were examined for their influence on posture and force output. It is hypothesized that spinal flexion will become more prominent and force output will decrease following fatigue. It is also hypothesized that a reduced level of sagittal hip mobility will result in a greater degree of spinal flexion and decreased force output during simulated scrumming. As a result, an increase in hip mobility and muscular endurance could be prescribed to rugby players in order to decrease injury risk and improve performance.

2. Literature Review

2.1 – Rugby Intervertebral Disc Herniation Risk:

Given that the scrum is only comprised of eight forwards (of the 15 players on the field), it is not a risk factor for all participants but poses a high threat of spinal injury, particularly in the front row (players 1,2,3; figure 1) (Brooks & Kemp, 2011). Intervertebral disc (IVD) herniation is a significant injury risk in rugby, accounting for 3.2% of injuries in professional rugby, double the injury rate than the well publicized risk of concussions in rugby (1.6%) (Holtzhausen, Schwellnus, Jakoet, & Pretorius, 2006). One study looking at the cervical spine of front row forwards found that 20-37 year old rugby players had a higher rate of IVD bulge (48% vs. 7%) and IVD herniation (29% vs. 3%) than healthy age matched controls in the population, respectively (Berge, Marque, Vital, Sénégas, & Caillé, 1999). Further research found that cervical IVD degeneration was significantly greater in rugby players than non-players, but, interestingly, they did not exhibit more significantly more symptoms (Hogan, Hogan, Vos, Eustace, & Kenny, 2010). It also appears as though rugby players have an inferior sense of cervical repositioning than non-rugby players (Lark & McCarthy, 2007; Pinsault, Anxionnaz, & Vuillerme, 2010). Though hyperflexion in the cervical spine due to scrum collapse has been extensively cited as an acute injury risk (Kumano & Umeyama, 1986; Scher, 1991; Trewartha et al., 2014) the rate of injury in the cervical spine appears to be decreasing with new rules implemented (Bohu et al., 2009).

Rugby players are at significant risk of chronic injury to the spine, particularly the lumbar spine, as well. One study found that lumbar IVD/nerve root injury was the rugby injury resulting in the greatest number of days absent from training (Brooks et al., 2005).

This can have significant implications for the future of professional athletes, as one study found that NFL athletes with lumbar IVD herniations were significantly less likely to be drafted than those without (Schroeder et al., 2014). Given the high impact nature of both sports, it can be postulated that this applies to rugby players as well. Further, it has been found that rugby players are more likely to sustain spinal injuries as the number of years and level of participation increases, therefore protecting the longevity and performance of rugby players is important, as their injury risk increases over time (Hogan et al., 2010).

2.2 - Force Production in the Rugby Scrum:

The magnitude and direction of force production in a rugby scrum is crucial, as this is one of the primary factors that dictate success in the scrum. Several studies have observed force production in an eight man scrum (Cazzola et al., 2014; Preatoni et al., 2013; Saletti et al., 2013) as well as individual scrumming (Cazzola et al., 2015; Jougla, Micallef, & Mottet, 2010; Milburn, 1990; Quarrie & Wilson, 2000).

In the past, scrum forces have generally followed a characteristic curve as the two forward packs would line up approximately 0.29m-0.52m away from the middle of the scrum and engage with a significant impulse (Preatoni et al., 2013). This impulse would result in an initial compression force peak, followed closely by a rebound phase, which is then followed by a consistent sustained push phase as outlined by Figure 2 (Trewartha et al., 2014). Over the last few years, rule changes have been implemented to attempt to reduce the impact peak (Bohu et al., 2009; Cazzola et al., 2015; Preatoni et al., 2013). This has resulted in shifting the referee calls that initiate the scrum. Prior to 2011/2012 the referee would instruct the front row to "crouch" (lower themselves into their scrumming position), “touch” (touch the shoulder of the front row across from them), “pause” (prepare for engagement) and “engage” (forcefully engage with the opposite pack). In 2012/2013, the International Rugby Board removed the “pause”, in order to speed up the scrums given the high number of scrums in a game (Fuller et al., 2007). In 2013/2014 they replaced the “touch” with “bind”, forcing the front rows to bind against the opposite team thereby reducing the distance of the engagement phase. The new cadence is therefore – “crouch”, “bind”, “set” (Appendix F), which was been shown to reduce the impact peak but not influence the sustained push phase of the scrum (Cazzola et al., 2015).

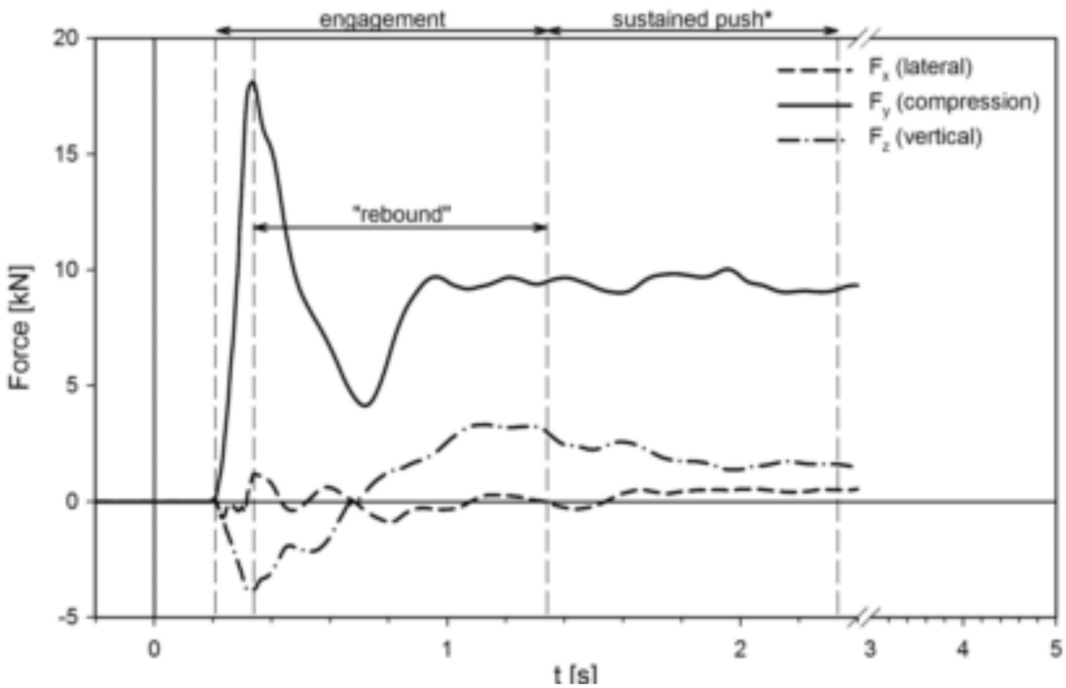

Figure 2: An example of whole pack force output using previous referee cadence for engagement. (Trewartha et al., 2014)

Another method that has been suggested to reduce the impact forces of the scrum is a sequential binding of different positions in the scrum. For example, the front row (players 1,2,3) would engage, followed by the locks (players 4,5), followed by the loose forwards (players 6,7,8) (Figure 1). This has shown to reduce the impact peak of the scrum (16,500N to 14,200N), however, it has also increased the off-axis forces, spinal misalignments and overall stability of the scrum (Trewartha et al., 2014). As a result this method has not been adopted.

Milburn (1990) was the first to look at whole pack scrum forces, finding axial compression forces in the range of 4430N (High school) to 7980N (International). Over time there has been a trend towards increased force production (Trewartha et al., 2014). Under the previous scrumming laws, Preatoni et al. (2013) measured the impact peak of a rugby pack to be in the range of 8,700N (Women) to 16,500N (International) with a sustained push range of 4,800N (Women) to 8,300N (International) (Figure 2). They also found that forces normalized to body weight did not differ between packs of lower skill levels (School, Community, Academy, Women) but did differ significantly from high skill levels (Elite and International). Therefore the increased force output of elite packs is not solely attributable to increased pack mass.

In terms of individual contribution to the scrum, Milburn (1994) determined that the relative force contributions of the scrum were: Front Row (players 1,2,3) – 37%; Second Row (players 4,5) – 42%; Flankers (players 6,7) – 9% and 8-man (player 8) – 12% (Figure 1) by subtracting each of these groups from the whole scrum and comparing to the forces produced by the whole scrum. Quarrie and Wilson (2000) determined that the force produced by the whole scrum was equivalent to 65% of the sum of the individual forces. They also found that packs that exerted the greatest force would not necessarily have the greatest summed individual forces, but used the individual forces to the greatest extent. This indicates the importance of the technique and coordination of the pack.

When measuring individual axial compression force during the sustained phase, Quarrie and Wilson (2000) found no statistically significant difference between forward position groups, but did indicate that force output by props (1420N) and locks (1450N) were higher than loose forwards (1270N) during the sustained phase of scrumming. Peak compression force of individuals during the impact phase has been found to be in the range of 2,800N – 3,100N (Cazzola et al., 2015; Sharp, Halaki, Greene, & Vanwanseele 2014).

Given the nature of the scrum, it can be suggested that forces not in the horizontal direction are wasteful and do not contribute to the success of the scrum, however, these forces do exist. Downward forces of approximately 1000N-2000N representing 20-24% of compression force have been recorded during the engagement phase (Milburn, 1990; Preatoni et al., 2013). Some researchers have postulated that this downward force may be attributed to scrum machine stability and suggest that live scrumming might not see the same magnitude of downward force (Trewartha et al., 2014). Preatoni et al. (2013) also determined that this downward force in the engagement phase would become a slight upward force during the sustained push phase. Lateral forces have been generally found to be inconsistent in magnitude and direction and represent instability and inefficiency of the scrum (Preatoni et al., 2013; Trewartha et al., 2014).

2.3 - Hip flexor Tightness and Back Pain/Flexion:

Though some researchers still refer to the hip flexor muscle complex as the illiopsoas, this is somewhat of a misnomer given that the psoas and illiacus have a different structure and function (Sajko & Stuber, 2009). The psoas major originates from the transverse processes, bodies and IVDs of the 12th thoracic and five lumbar vertebrae, whereas the illiacus originates from the iliac fossa. Further, the psoas major is innervated by the lumbar plexus, whereas the illiacus is innervated by the femoral nerve. Both insert onto the lesser trochanter of the femur, which may explain why they are often described as one unit. This is the primarily musculature responsible for flexion of the hips.

In the current study, hip mobility is defined as maximum active and passive range of motion (ROM) achievable at the hip in the sagittal plane. Hip ROM is likely attributable to activity level, genetic factors and environmental factors such as culture (Sjolie, 2004). Hip ROM is also often associated with a variety of conditions, including low back pain (Roach, San Juan, Suprak, & Lyda, 2013; Sjolie, 2004). Given that the psoas major spans from the thoracolumbar region to the femur attachment, it can act as a major compressor of the lower back (Bogduk, Pearcy, & Hadfield, 1992). Cholewicki and McGill (1996) argue that this spinal compression can improve spinal stability, as bilateral co-contraction of the psoas majors can provide equal and opposite moments on the spine. Too much spinal compression, however, as a result of tight hip flexors, can cause low back pain (Van Dillen, Bloom, Gombatto, & Susco, 2008). One study found that manual fascial lengthening therapy of the hip flexors successfully reduced back pain and improved passive ROM in a population with low back pain (Avrahami & Potvin, 2014). Further, low back pain has been associated with decreased hip ROM in adolescents (Sjolie, 2004).

Research by Dolan and Adams (1993) found that poor sagittal mobility in the hips and lumbar spine led to greater spine flexion in a variety of bending and lifting activities. This has also been found in a golfing population (Kim, You, Kwon, & Yi, 2014) and in sitting (Kang et al., 2013) as decreased mobility in the hips led to greater lumbar spine flexion. Lumbar flexion has been heavily linked to low back injury, as flexion increases intradiscal pressure and reduces the force required to damage the annulus of the IVD (Wade et al., 2014; Weinhoffer, Guyer, Herbert, & Griffith, 1995). Mechanically, a combination of flexion and compression can cause the IVD to prolapse backwards, which is generally a precursor to disc herniation and damage of the osteoligamentous lumbar spine (Dolan & Adams, 1998; Callaghan & McGill, 2001) which is an important consideration in the rugby scrum.

2.4 - Quadriceps Fatigue and Spinal Flexion:

Fatigue can be defined as "any exercise-induced loss of ability to produce force within a muscle or muscle group" (Taylor, Todd, & Gandevia, 2006, p.83). Understanding scrumming in the context of fatigue is crucial, as rugby is a highly physically demanding sport (Roberts et al., 2010). Jougla et al. (2010) showed that individual scrumming force decreased more following active recovery (running for 30s at 50% maximal aerobic speed) than following passive recovery (standing still) in a rugby specific protocol; an indicator that fatigue can decrease muscular force during a rugby match or training.

Little research has examined spinal posture following fatigue in the rugby scrum but much can be gleaned from other postural studies using quadriceps fatigue. Performance research of firefighters determined that spinal flexion increased following a 3-minute stair-climbing task in a firefighting specific protocol such as a mannequin drag, forcible entry and ceiling breach (Gregory et al., 2008). This is echoed by findings that individuals transitioned from squat lifting (knees bent, straight back) to stoop lifting (knees straight, flexed back) as the quadriceps became more fatigued in a lifting task (Trafimow et al., 1993). As a result it is reasonable to postulate that spinal flexion may increase in the rugby scrum following fatigue.

2.5 - Hip Complex Range of Motion Testing:

Hip joint ROM is generally measured with the contralateral hip stabilized to the table. This is to avoid pelvic tilting which can induce lumbar spine flexion or extension and artificially demonstrate an increased ROM at the hips (Reese & Bandy, 2010). Research has shown that this grossly inflates hip ROM when using a goniometer (Nussbaumer et al., 2010) and that up to one quarter of the ROM can often be attributed to pelvic tilt (Bohannon, Gajdosik, & LeVeau, 1985). For this reason clinicians must be extremely careful to stabilize the pelvis during ROM tests.

Intra-rater reliability of hip joint ROM tests is generally good when performed on healthy adults. Clapper and Wolf (1988) obtained interclass correlation coefficient (ICC) values of .95 and .83 for active hip ROM flexion and extension, respectively. Walker, Sue, Miles-Elkousy, Ford, and Trevelyan (1984) reported a Pearson's correlation coefficient of > .81 for all hip ROM tests while inter-rater reliability appears to be significantly lower (ICC values of .55-.74) (Ahlbaeck & Lindahl, 1964). This is of less concern to the current study, as the same clinician will be performing all hip ROM measurements.

The Thomas test has been extensively used in clinical settings to measure the muscle length of the hip complex. Many studies looking at both intra- and inter-rater reliability of the Thomas test have obtained high ICC values when looking at healthy subjects (Aalto, Airaksinen, Härkönen, & Arokoski, 2005; Godges, MacRae, & Engelke, 1993; Winters et al., 2004) and athletic subjects (Harvey, 1998; Wang, Whitney, Burdett, & Janosky, 1993). With respect to intra-rater reliability of athletes, Wang et al. (1993) obtained an ICC of 0.97 in a runners for both the dominant and non-dominant legs. Harvey (1998) obtained an ICC in the range of 0.91-0.94 for elite athletes from tennis, basketball, rowing and running. Similar results were obtained with regular healthy adults, obtaining an ICC of greater than .80 in all cases (Aalto et al., 2005). Inter-rater reliability has also proven to be high in healthy populations, with ICC values in the range of 0.74-0.98 (Aalto et al., 2005; Clapis, Davis, & Davis, 2008; Winters et al., 2004). Both intra- and inter-rater reliability have yielded lower ICC values in children and individuals with musculoskeletal conditions (Reese & Bandy, 2010), but this likely speaks more to the variation in the participants than the reliability of the test. Overall, in athletic and healthy populations it appears that the Thomas test is a reliable test to determine muscle length of hip complex.

3. Methods

3.1 Participants

Participants were experienced rugby forwards between the ages of 18 and 41. There were 16 males recruited for this study from the Wilfrid Laurier University and Waterloo County Club rugby programs. They all had at least 4 years of experience playing in the rugby scrum for a full rugby season and had not experienced a significant spinal or hip injury in the past year. Participants were given a screening questionnaire to determine if they were eligible to participate in the study that included demographic, positional and rugby experience information. Each individual was required to fill out a consent form describing the study protocol and any risks they may experience. Wilfrid Laurier University Ethics Board reviewed and approved of the study prior to data collection.

3.2 Overview of Protocol

At the start of collection, measures of hip mobility were taken with the assistance of a physiotherapist. Each measure of hip mobility was taken three times on each side and the average of the three measures was taken. The first measurement was an active hip flexion ROM, which consisted of the individual flexing their leg to the maximum angle attainable in a supine position on the lab bench with the contralateral leg remaining flat on the bench (Figure 3). The angle was taken using a goniometer landmarking the lateral midline of the trunk (stationary arm), greater trochanter of the femur (axis) and lateral midline of the femur towards the femoral epicondyle (moving arm) (Figure 3) (Reese & Bandy, 2010). This measurement was repeated with the physiotherapist passively moving the leg through maximum ROM (Figure 4). In both cases, care was taken to limit flexion to the sagittal plane, avoiding abduction, and to avoid posterior pelvic tilt, which could artificially appear to increase ROM.

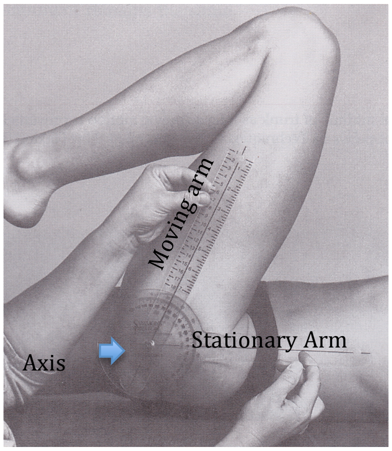

Figure 3: Measure of hip flexion ROM using a goniometer. (Reese & Bandy, 2010)

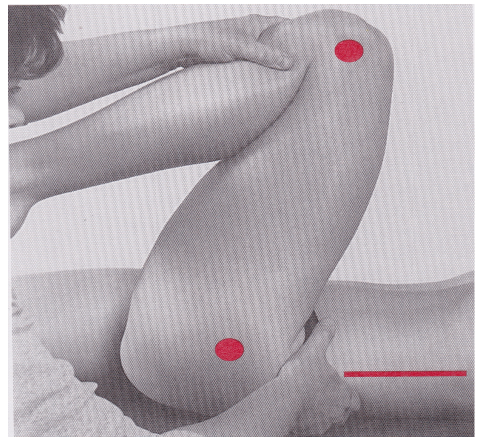

Figure 4: Land-marking during passive hip flexion (Reese and Bandy, 2010)

The second measure of hip ROM was hip extension (Figure 5). This was conducted with the patient lying prone and the knee flexed to avoid testing shortness of the biceps femoris. Again, both active and passive measures of hip ROM were taken with the pelvis stabilized to avoid lumbar spine extension and the contralateral leg remained flat on the bench. The goniometer landmarks were once again the lateral midline of the trunk (stationary arm), the greater trochanter of the femur (axis) and the lateral epicondyle of the femur (moving arm) (Figure 6) (Reese & Bandy, 2010).

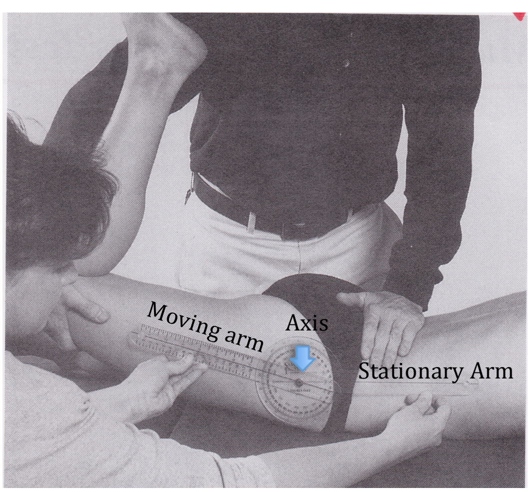

Figure 5: Measuring hip extension ROM using a goniometer. (Reese & Bandy, 2010)

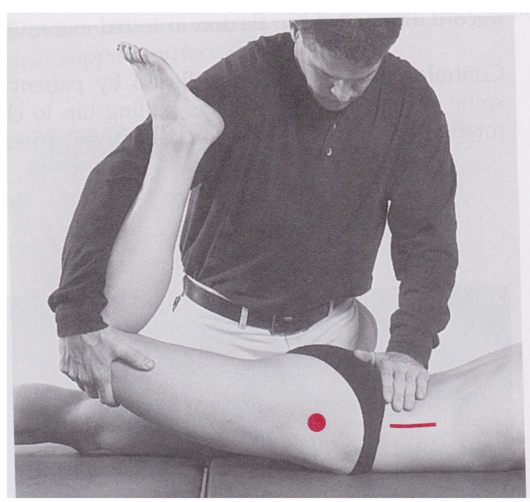

Figure 6: Land-marking during passive hip extension. (Reese & Bandy, 2010)

The last hip ROM measurement conducted was the Thomas test (Figure 7). The Thomas test is performed with the individual lying supine and the contralateral hip flexed towards the chest. The individual was instructed to flex their contralateral hip only enough to flatten the lumbar spine against the support surface, and the ipsilateral hip angle was measured. Again, the landmarks were the lateral midline of the trunk (stationary arm) greater trochanter of the femur (axis) and lateral epicondyle of the femur (moving arm) (Figure 8) (Clapis et al., 2008; Reese & Bandy, 2010). The angle was recorded as the angle above or below the horizontal axis, with a greater angle below the horizontal indicating a greater degree of flexibility.

Figure 7: Measuring the ROM with a goniometer during the Thomas test. (Clapis, Davis, & Davis, 2008)

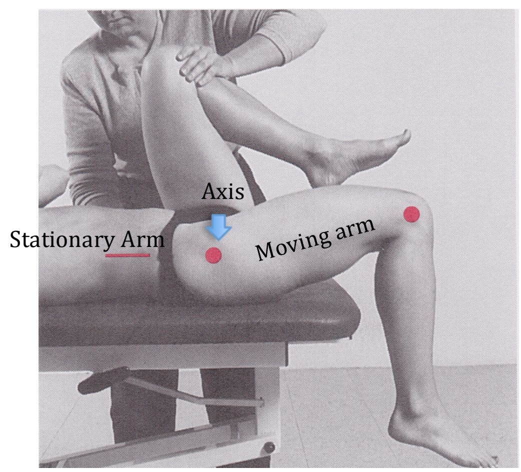

Figure 8: Land-marking during the Thomas test. (Reese and Bandy, 2010)

Following hip ROM measurements, participants were instrumented with electromyography (EMG) electrodes and performed maximum voluntary contractions (MVCs) as described in section 3.3.1. They were then instrumented with the electromagnetic motion capture system on the spine as described in section 3.3.2. A relaxed neutral standing trial was collected in order to normalize spine angle data.

The individuals were then able to familiarize themselves with the scrum machine by performing 3-5 submaximal practice scrums using the protocol while no data was collected in order to warm up. Individuals were instructed to push straight ahead on fixed height scrum pads rather than producing shear forces (Quarrie & Wilson, 2000). When the recorded trials were to begin, the individual set up approximately a 0.5m away from the scrum pad, crouching into a semi-squat scrum position. When the participants indicated that they were ready, an audio recording for the referee cadence of "crouch, bind, set" would prompt their engagement into the scrum machine (Appendix F). The individuals were encouraged to push forcefully for 5 seconds (Figure 9) and a "stop" call indicated the end of the scrum. Five repetitions of this protocol occurred with 1-2 minutes of passive recovery (standing) in between trials (Cazzola et al., 2015; Preatoni et al., 2013; Swaminathan, Williams, Jones, & Theobald, 2016).

Figure 9. Individual Scrum Set-Up.

Following the initial scrumming condition, participants performed a wall sit to fatigue. The participants were instructed to sit against the wall with the knees and hips at a 90° angle until they are no longer able to maintain this posture (Wahl & Behm, 2008). The trial was finished if participants deemed themselves unable to continue or were unable to maintain their posture near the 90° angle as visually determined by the researcher. Participants were allowed to readjust their position in order to return to the 90° angle throughout the trial to account for the poor friction of the foam surface they were against. EMG data from four quadriceps muscles (see section 3.3.1) were collected to verify that they experienced muscular fatigue.

The second scrumming session took place immediately following the fatiguing protocol. No practice occurred prior to this session and participants performed five scrumming repetitions using the same audio cues as described above. In order to maintain fatigue the participants had a minimal rest interval (5 seconds) in between trials, enough time to return to standing and prepare themselves for the following trial. An overview of the protocol can be observed in Figure 10.

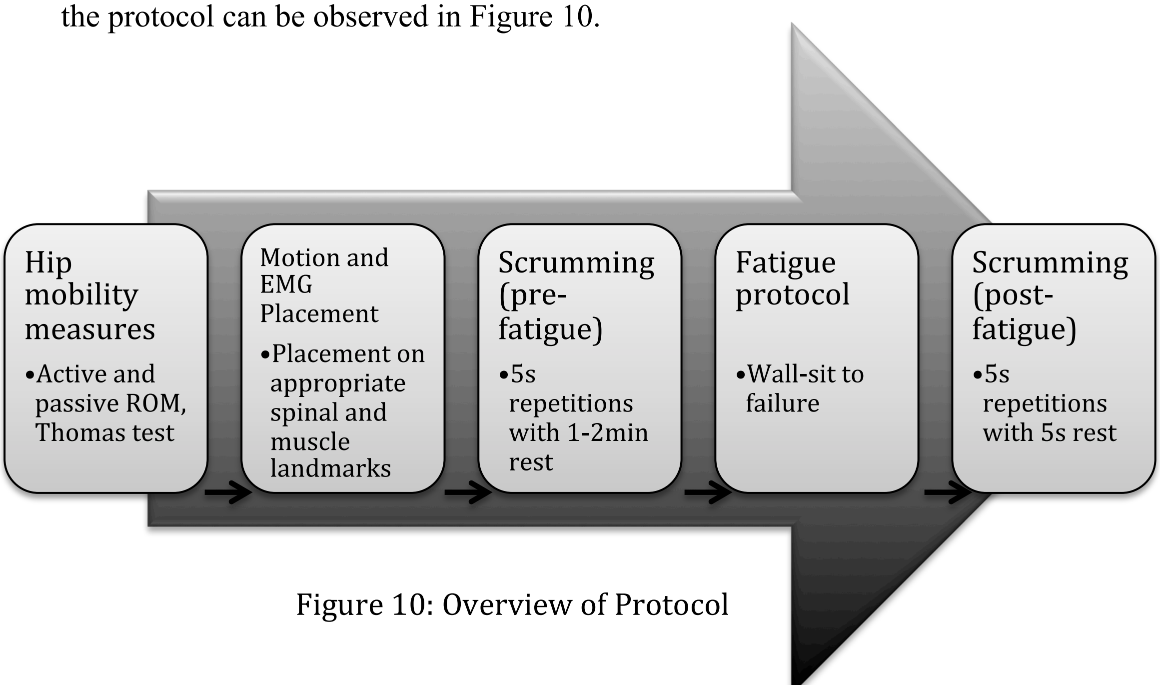

Figure 10: Overview of Protocol

3.3 Instrumentation and Data Processing

3.3.1 Electromyography

3.3.1.1 Electromyography Instrumentation

To assess muscle activity during the scrumming and fatigue trials, surface EMG was collected from quadriceps and trunk musculature. Prior to electrode placement, hair was shaved, if necessary, and then the skin was cleansed with 70% isopropyl-rubbing alcohol in order to prep the skin surface over each muscle. Two pairs of Ag-AgCl electrodes (Ambu Blue Sensor, Denmark) were placed bilaterally over the quadriceps, specifically the Vastus Medialis (VM) and Vastus Lateralis (VL). The electrodes were placed approximately 9cm and 7cm above the superior border of the patella, on the anterior lateral and anterior medial sides of the thigh, for the VL and VM, respectively (Mathur, Eng, & MacIntyre, 2005). Four pairs of electrodes were placed bilaterally on the trunk musculature as follows: Lumbar Erector Spinae (LES) was placed 3cm lateral to the L3 spinous process, Thoracic Erector Spinae (TES) was placed 5cm lateral to the T9 spinous process, Rectus Abdominis (RA) was placed 3cm lateral to umbilicus and External Oblique (EO) was placed 15cm lateral to umbilicus (McGill, Norman, & Cholewicki, 1996). Last, electrodes were placed on the left anterior superior iliac spine and right tibial tuberosity as reference electrodes. All EMG data were bandpass filtered from 10 to 1000Hz, amplified (Bortec, Calgary, Alberta, Canada) and sampled at 2048Hz. Raw EMG data were full-wave rectified and filtered using a single-pass second-order Butterworth filter with a low-pass cut off of 2.5Hz to create a linear envelope. The linear enveloped data were further normalized to the MVC performed for each muscle (described in 3.3.1.2). Data were visually inspected and omitted if significant nonbiological noise was present. For the fatigue trials, raw EMG from the VL and VM were transformed into the frequency domain using a fast Fourier transform (FFT) to calculate the median power frequency (MdPF). A significant decrease in the MdPF from the start of the fatiguing trial to the end was used as an indicator of muscular fatigue.

3.3.1.2 Maximum Voluntary Contractions

Following electrode placement, MVCs were collected to normalize the EMG data (Appendix D). Prior to collecting MVCs, the signal gain was adjusted to ensure an adequate signal level. In order to test the Erector Spinae (ES) musculature (LES and TES), a maximal Biering-Sorensen back extension was performed (Latimer, Maher, Refshauge, & Colaco, 1999). This was done with the participant's lower body secured to the edge of the physiotherapy table and their torso hanging off the table. The researcher then resisted the maximal back extension force by the participant. The abdominal muscle MVCs (RA and EO) were tested using a modified sit-up position with the torso flexing forward, lateral bending and twisting to the left and right with resistance by the researcher to allow no movement. The quadriceps muscles (VM and VL) MVCs were measured with the participant seated with the hips and knees at 90°. Participants were instructed to extend their knee against resistance provided by a strap held by the researcher. Exertions were not restricted to a set time but lasted on average 3-5 seconds per muscle - with the main goal being to achieve a maximal contraction. Each protocol was repeated, adjusting the gain until a desired signal level was achieved and the participant was able to achieve their maximal contraction. Rest time between MVCs was between 1-2 minutes. During each MVC participants were instructed to provide maximal effort and were verbally encouraged. MVC trials were processed in the same manner as all scrumming trials (described in section 3.3.1.1) and the maximum value within the MVC trial was used for normalization purposes.

3.3.2 Kinematics

To capture lumbar, thoracic and cervical flexion angles during scrumming, an electromagnetic motion capture system was used (Liberty, Polhemus, Colchester, Vermont, United States). The intersection of two markers was used to determine the spine angle in each spinal region. Four sensors were placed on the body at the L5/S1 (lumbosacral) joint, T12/L1 joint, C7/T1 joint and the C1/occipital joint. The angle between the occipital/C1 and C7/T1 represented the cervical spine flexion angle, the angle between C7/T1 and T12/L1 markers represented the thoracic spine flexion angle and the angle between the T12/L1 and L5/S1 markers represented the lumbar spine flexion angle. Prior to the start of the scrumming protocol, each participant performed a standing trial with eyes fixed forward to determine neutral spine posture. Motion data were sampled at 32 Hz, and dual-pass filtered with a low-pass cut-off of 6Hz.

3.3.3 Scrum Machine Force

The force applied to the scrum machine was measured using a uniaxial load cell mounted to the framework of the scrum apparatus (Vernier, Beaverton, Oregon, United States) capable of measuring forces of up to 3500N compression. Force was sampled at 500Hz for the pre-wall sit scrumming trials and 250Hz for the post-wall sit scrumming trials (due to this being the maximum sample rate available for a 90s trial - Appendix C).

3.4 Windowing Data

Spine angle data were windowed first given the characteristic plateaus in the lumbar and thoracic region during the contact and pre-contact phases (Figure 11 - Top). A manual pulse, synchronized to the EMG and motion data, was used to give a spike signal, and, as a result, an approximate time point of the crouch, the bind and the end of the trial. Though the pulse was used as a guideline, the windowing was done using the motion data and accelerometer peak as this represents the actual movement of participant.

The beginning of the pre-contact phase was determined using visual inspection of the start of the first lumbar spine plateau. The pre-contact phase finished approximately 0.6s (20 samples) prior to impact as determined using the accelerometer peak. Similarly, the contact phase then began approximately 0.6s (20 samples) following impact (using the accelerometer peak), and was terminated when the lumbar plateau stopped, as determined by visual inspection (Figure 11 – top). Average, maximum flexion and standard deviation of these regions were taken over both of these phases for spine motion data. These windows were adjusted from a sample rate of 32Hz to a sample rate of 2048Hz by multiplying by 64 in order to use the same windows for the EMG data (Figure 11 – Middle). Average was taken across both the pre-contact and contact phases for EMG to achieve average activation.

Finally, the force data was windowed separately. The maximum over the entire trial was taken to capture the impact peak. The sustained push began just following the rebound phase (Figure 2) and terminated at the end of the plateau as determined by visual inspection (Figure 11 – Bottom). Average and standard deviation were taken from the sustained push region.

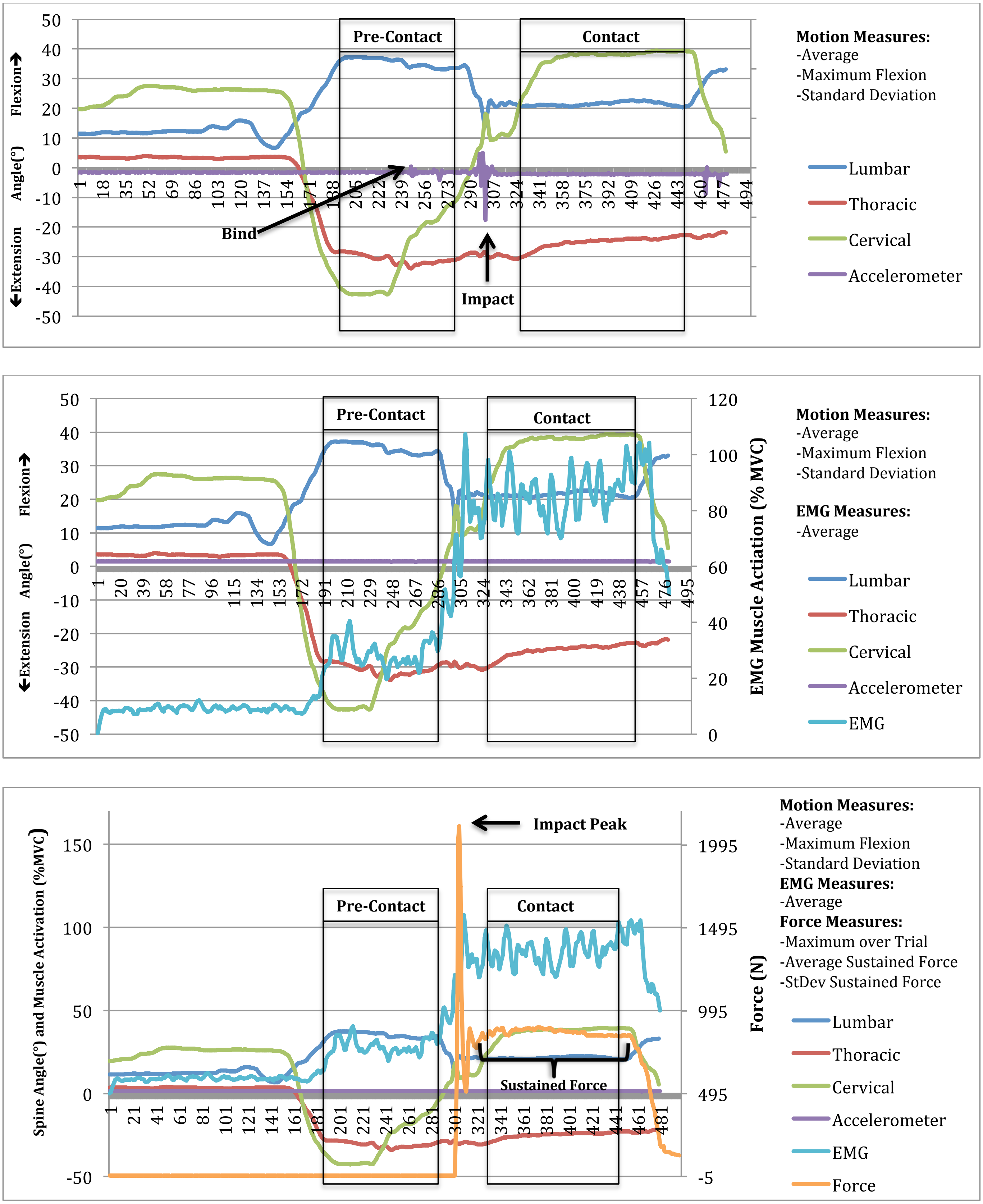

Figure 11. Windowing of Spine Motion data (top) EMG data (Middle) and Force data (Bottom).

3.5 Statistical Analysis

To determine the effect of wall sit fatigue, a one-way repeated measures analysis of variance (ANOVA) was conducted (the factor being level of fatigue: pre versus post-wall sit) on the following dependent variables: scrum force output (impact peak, average sustained push force and standard deviation of sustained push force), mean, maximum flexion and standard deviation of spinal flexion across spinal regions, and mean muscle activation for the muscles being measured in section 3.3.1.

In order to assess the role of repetitive scrumming, the first and fifth scrum trial of the pre-wall sit condition and the first and fifth scrum trial in the post-wall sit condition were each compared using a related samples t-test. The following dependent variables were examined: scrum force output (impact peak, average sustained push force and standard deviation of sustained push force), mean, peak and standard deviation of spinal flexion across spinal regions, and mean muscle activation for the muscles being measured in section 3.3.1.

In order to assess the relationship between hip mobility and both force output and spinal flexion, each measure of hip mobility was correlated to the average force output and spinal flexion measures taking an average of the five pre-wall sit trials. Further, in order to determine the relationship between anthropometrics and performance measures such as wall sit, each of these measures were correlated to the average force output and spinal flexion measures taking an average of the five pre-wall sit trials to determine the a relationship between these variables.

An alpha level of 0.05 was considered significant for all tests and SAS was used to conduct all statistical tests.

4. Results

4.1 Participant Information

There were 16 rugby athletes included in this study from the Wilfrid Laurier Varsity Ruby team and Waterloo County Club Team. In terms of primary position there were: 3 Props (1,3), 4 Hookers (2), 3 Locks (4,5) and 6 Loose Forwards (6,7,8) (numbers in brackets refer to positions in Figure 1). The participants were an average of 21.9 (SD = 5.6) years old, 98.4(SD = 7.1)kg, 183.2(SD = 7.2)cm, BMI of 29.4(SD = 2.8)m/kg^2, with 8.4 years(SD = 4.6) of rugby experience and 8.0 years (SD = 4.1) of forward experience. The average wall sit time was 236 (SD = 96.2) seconds (Table 1).

4.2 Wall Sit Fatigue

4.2.1 Effect of Wall Sit Fatigue on Spine Angle

4.2.1.1 Effect of Wall Sit Fatigue on Pre-Contact Spine Angle

A significant effect of wall sit fatigue was found with respect to average angle and maximum flexion angle in the lumbar (average: $p = 0.0027$; maximum: $p = 0.0032$) and cervical (average: $p < 0.0001$; maximum: $p < 0.0001$) regions of the spine during the pre-contact phase (Figure 12). For the lumbar region, the average spine angle became significantly less flexed following wall sit fatigue (Pre: $\bar{x}$ = 33.1°, SD = 18.0°; Post: $\bar{x}$ = 25.6°, SD = 13.6°) and the maximum flexion angle was significantly lower (Pre: $\bar{x}$ = 39.1°, SD = 18.2°; Post: $\bar{x}$ = 31.7°, SD = 13.3°). In contrast, the average cervical region angle became significantly more flexed (Pre: $\bar{x}$ = -9.5°, SD = 12.0; Post: $\bar{x}$ = 2.3°, SD = 20.6) and the maximum flexion angle was significantly higher (Pre: $\bar{x}$ = 3.2°, SD = 11.2°; Post: $\bar{x}$ =14.4°, SD = 19.1°). No significant change occurred in average pre-contact spine angle (p = 0.49) or maximum flexion angle (p=0.63) in the thoracic region due to wall sit fatigue.

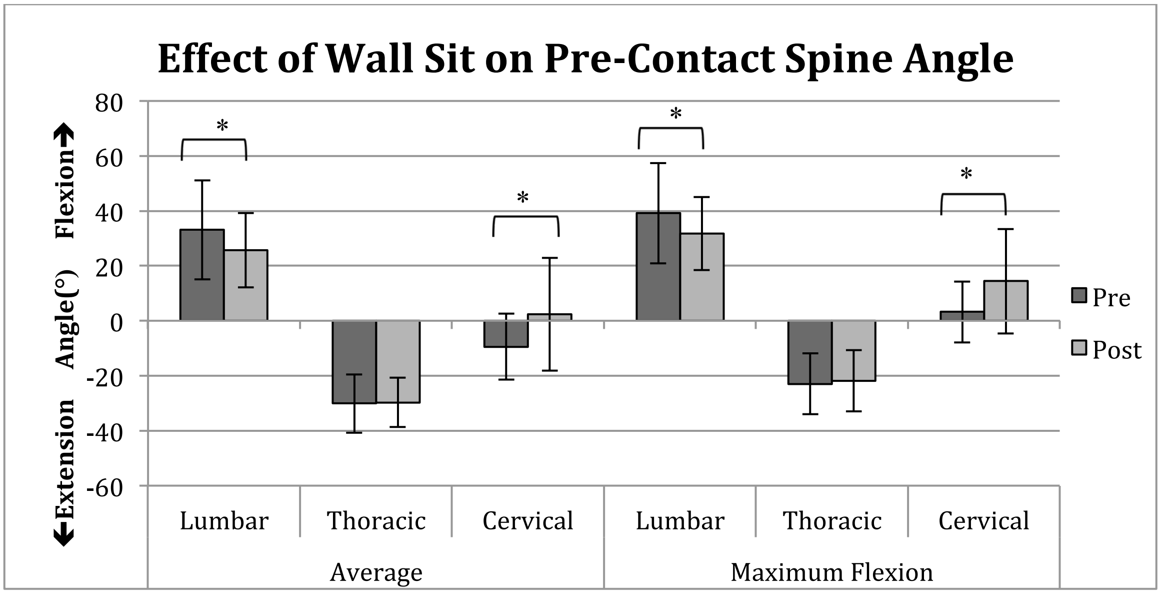

Figure 12. Effect of wall sit fatigue on average and maximum flexion angle during the pre-contact phase. Standard Deviation Bars Shown.

4.2.1.2 Effect of Wall Sit Fatigue on Contact Spine Angle

A significant effect of wall sit fatigue was found with respect to average angle ($p < 0.0001$) and maximum flexion angle ($p < 0.0001$) in the cervical region of the spine during the contact phase. Similar to during pre-contact, the average cervical angle became significantly more flexed (Pre: $\bar{x}$ = 21.0°, SD = 14.3°; Post: $\bar{x}$ = 32.0°, SD = 12.2°) and the maximum flexion angle was significantly higher (Pre: $\bar{x}$ = 26.0°, SD = 12.5°; Post: $\bar{x}$ = 36.0°, SD = 10.8°) following wall sit fatigue. No significant changes occurred in the lumbar region (average: p = 0.73; maximum: p = 0.96) or in the thoracic region (average: p = 0.67; maximum: p = 0.99) following wall sit fatigue in the contact phase.

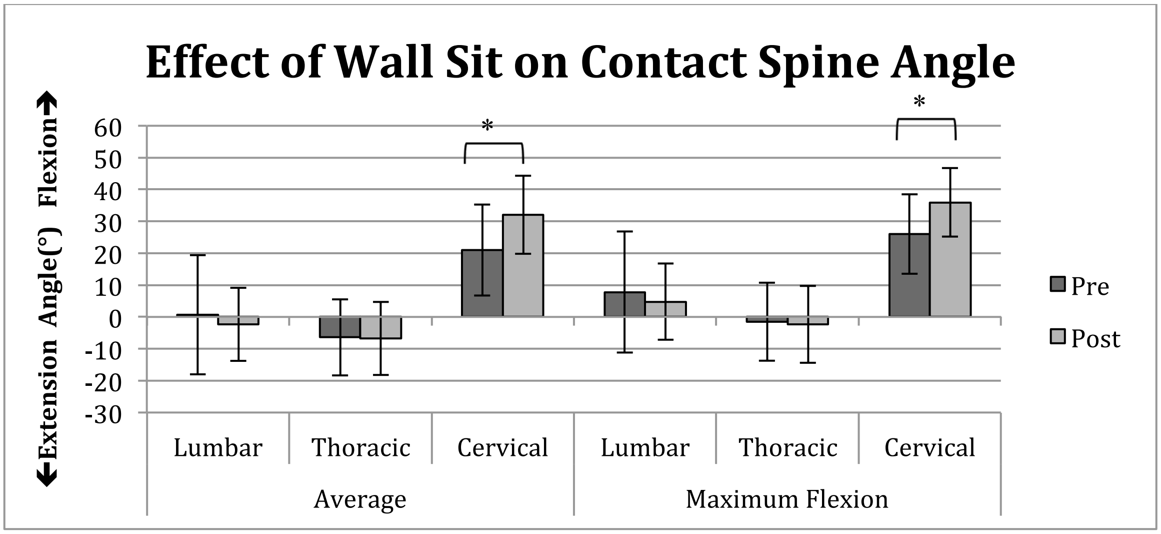

Figure 13. Effect of wall sit fatigue on average and maximum flexion angle during the contact phase. Standard Deviation Bars Shown.

4.2.1.3 Effect of Wall Sit Fatigue on the Standard Deviation of Average Spine Angle

No significant effect of wall sit fatigue was found for the standard deviation of the spine angles of the lumbar ($p = 0.74$), thoracic ($p = 0.33$) or cervical ($p = 0.24$) regions during the pre-contact phase.

Similarly, no significant effect of wall sit fatigue was found for the standard deviation of the spine angles of the lumbar ($p = 0.52$), thoracic ($p= 0.97$) or cervical regions ($p = 0.49$) during the contact phase.

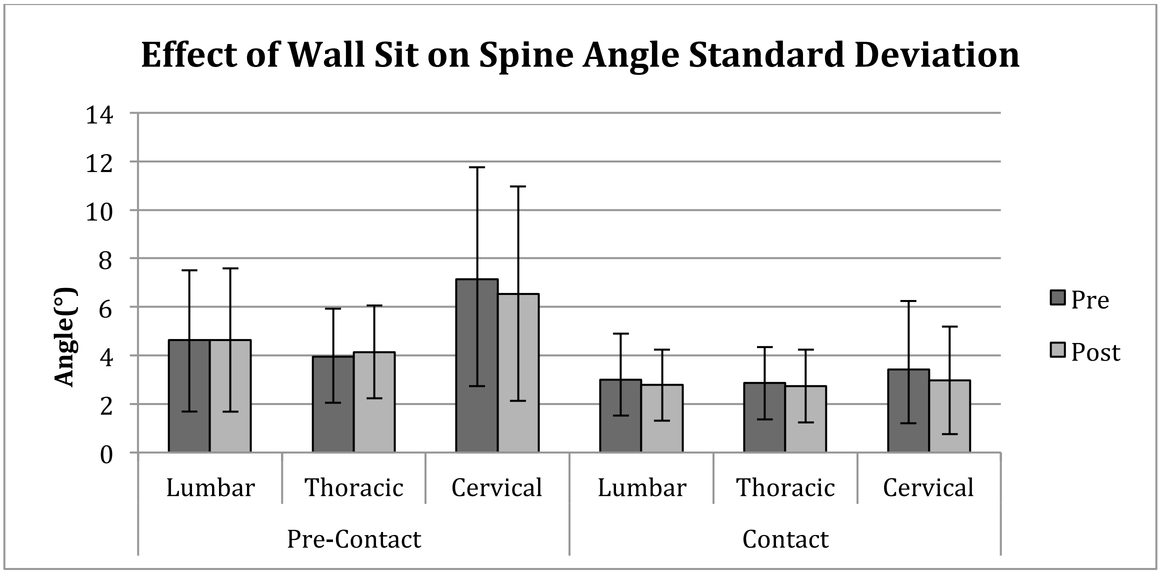

Figure 14. Effect of wall sit fatigue on standard deviation of average spine angle during the pre-contact and contact phase. Standard deviation bars shown.

4.2.2 Effect of Wall Sit Fatigue on Muscle Activation

4.2.2.1 Effect of Wall Sit Fatigue on Lumbar Muscle Activation

A significant effect of wall sit fatigue was found with respect to average LES activation during the pre-contact phase on both the left ($p = 0.0003$) and right ($p = 0.0218$) sides. During the pre-contact phase, the LES muscles became significantly more active in both the left (Pre: $\bar{x} = 20.1\%$ MVC, SD = 6.7%; Post: $\bar{x} = 22.6\%$ MVC, SD = 7.9%) and right (Pre: $\bar{x} = 18.8\%$ MVC, SD = 8.5%; Post: $\bar{x} = 24.0\%$ MVC, SD = 13.8%) sides. No significant effect of wall sit fatigue was found in the LES muscles during the contact phase in either the left ($p = 0.1549$) or right ($p = 0.1441$) sides.

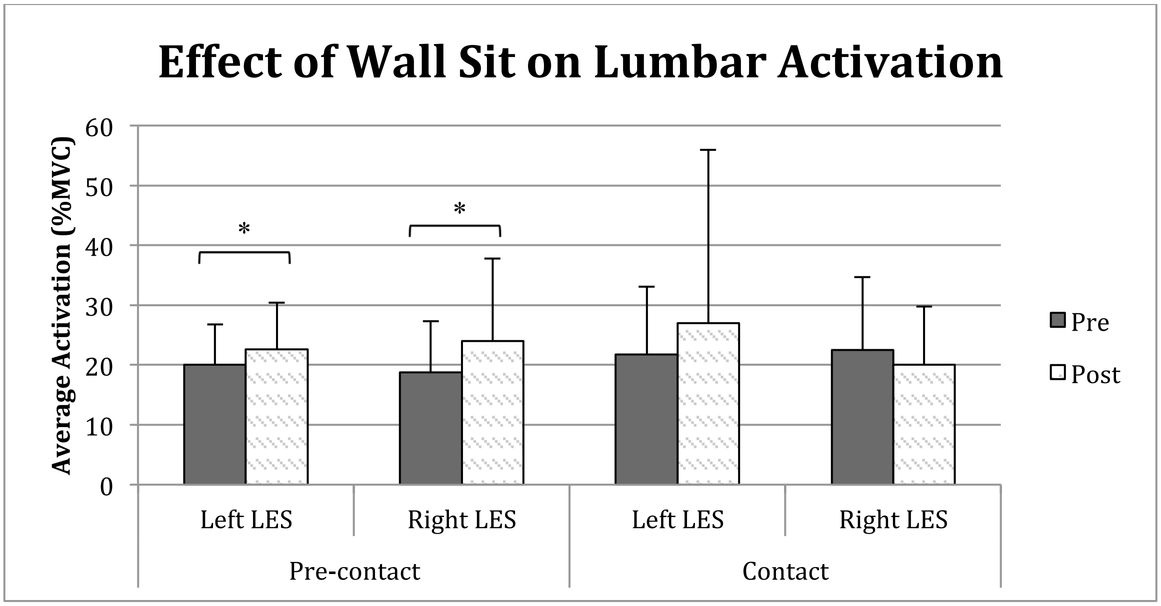

Figure 15. Effect of wall sit fatigue on LES activation during the pre-contact and contact phase. Standard deviation bars shown.

4.2.2.2 Effect of Wall Sit Fatigue on Thoracic Muscle Activation

A significant effect of wall sit fatigue was found with respect to average TES activation during the pre-contact phase for the left side ($p = 0.0279$) and both the left ($p = 0.0003$) and right ($p < 0.0001$) sides during the contact phase. During the pre-contact phase the left TES Muscle Activity decreased (Pre: $\bar{x}$ = 29.5% MVC, SD = 15.6%; Post: $\bar{x}$ = 25.5% MVC, SD = 12.2%) due to wall sit fatigue. Similarly, during the contact phase, the average TES muscle activity decreased on both the left (Pre: $\bar{x}$ = 50.7% MVC, SD = 39.1%; Post: $\bar{x}$ = 41.3% MVC, SD = 32.6%) and right (Pre: $\bar{x}$ = 51.4% MVC, SD = 31.8%; Post: $\bar{x}$ = 40.2% MVC, SD = 26.6%) sides due to wall sit fatigue. No significant changes occurred as an effect of wall sit fatigue in the right TES during the pre-contact phase ($p = 0.72$).

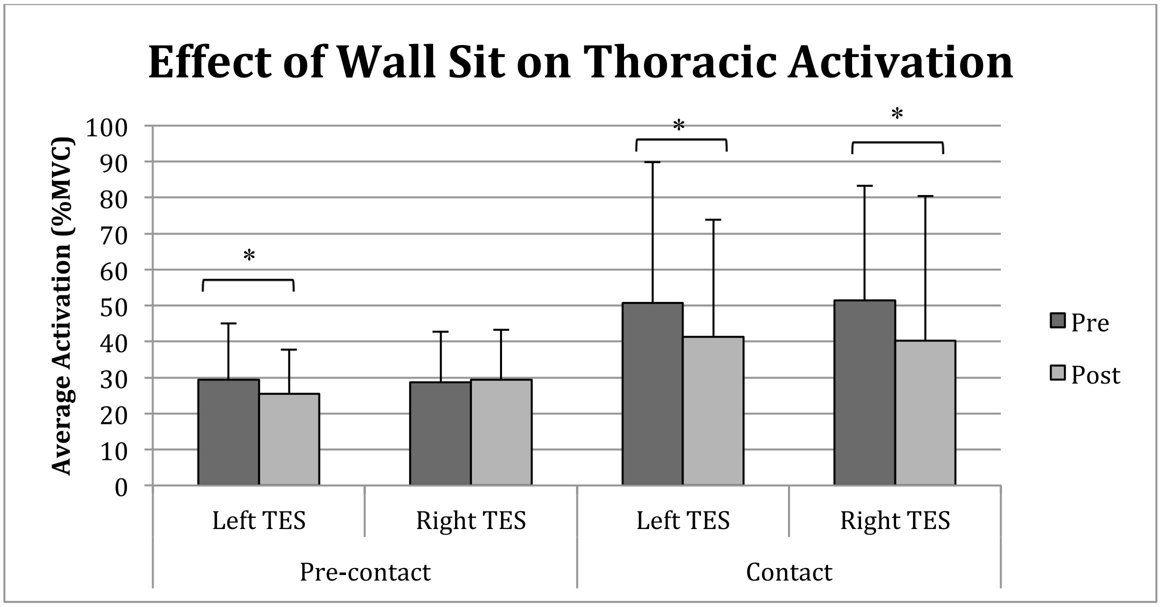

Figure 16. Effect of wall sit fatigue on TES activation during the pre-contact and contact phase. Standard deviation bars shown.

4.2.2.3 Effect of Wall Sit fatigue on Abdominal Activation

A significant effect of wall sit fatigue was found on average EO activation during the contact phase on both the left ($p = 0.0009$) and right ($p < 0.0001$) side. The EO muscles showed a decrease in activation in both the left (Pre: $\bar{x}$ = 16.9% MVC, SD = 9.8%; Post: $\bar{x}$ = 13.0% MVC, SD = 9.5%) and right (Pre: $\bar{x}$ = 18.4% MVC, SD = 7.2%; Post: $\bar{x}$ = 14.9% MVC, SD = 7.8%) sides during the contact phase due to wall sit fatigue. No significant effect was found for wall sit fatigue during the pre-contact phase on either the left ($p = 0.2208$) or right ($p = 0.8184$) EO.

There was no significant effect of wall sit fatigue on the left and right RA activation during the pre-contact phase ($p = 0.44$ and 0.16, respectively) or during the contact phase, ($p = 0.16$ and 0.20, respectively).

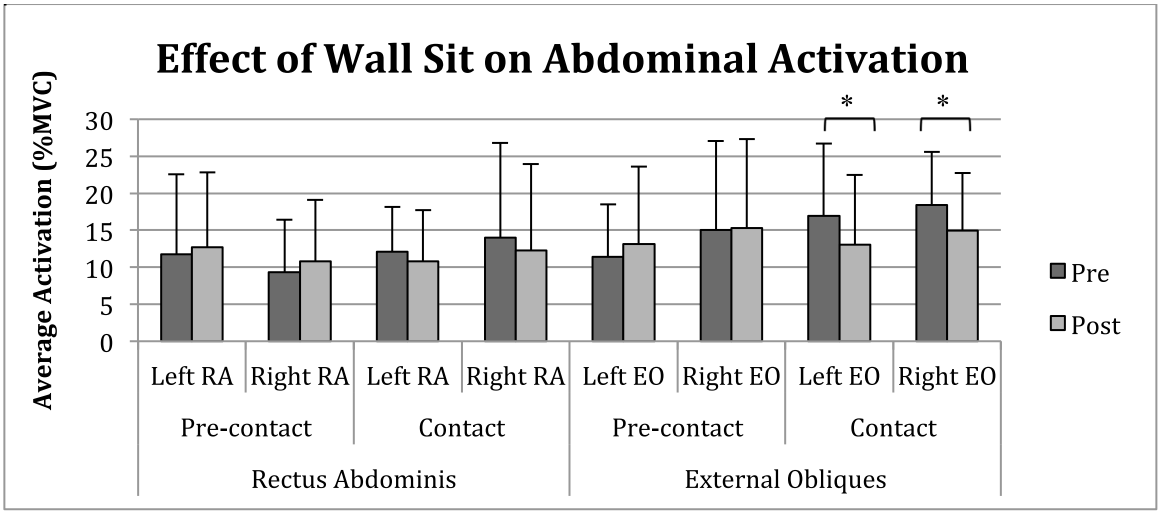

Figure 17. Effect of wall sit fatigue on abdominal activation during the pre-contact and contact phase. Standard deviation bars shown.

4.2.2.4 Effect of Wall Sit Fatigue on Quadriceps Activation

A significant effect of wall sit fatigue was found for all four quadriceps muscles during the pre-contact phase. On the left side, both the VM ($p < 0.0001$, Pre: $\bar{x}$ = 24.2% MVC, SD = 10.2%; Post: $\bar{x}$ = 29.5% MVC, SD = 10.6%) and VL ($p < 0.0001$, Pre: $\bar{x}$ = 21.8% MVC, SD = 10.0%; Post: $\bar{x}$ = 25.3% MVC, SD = 9.7%) showed a significant increase in average muscle activity due to the wall sit. Similarly, on the right side, both the VM ($p = 0.0003$, Pre: $\bar{x}$ = 29.4% MVC, SD = 10.5%; Post: $\bar{x}$ = 34.5% MVC, SD = 16.0%) and VL ($p < 0.0001$, Pre: $\bar{x}$ = 23.8%, SD = 7.1%; MVC, Post: $\bar{x}$ = 29.7% MVC, SD = 9.6%) muscles showed a significant increase in average muscle activity due to wall sit fatigue. There was no effect of wall sit fatigue on average muscle activation in either the left VM ($p = 0.39$), left VL ($p = 0.56$), right VM ($p = 0.50$) or right VL ($p = 0.19$) during the contact phase.

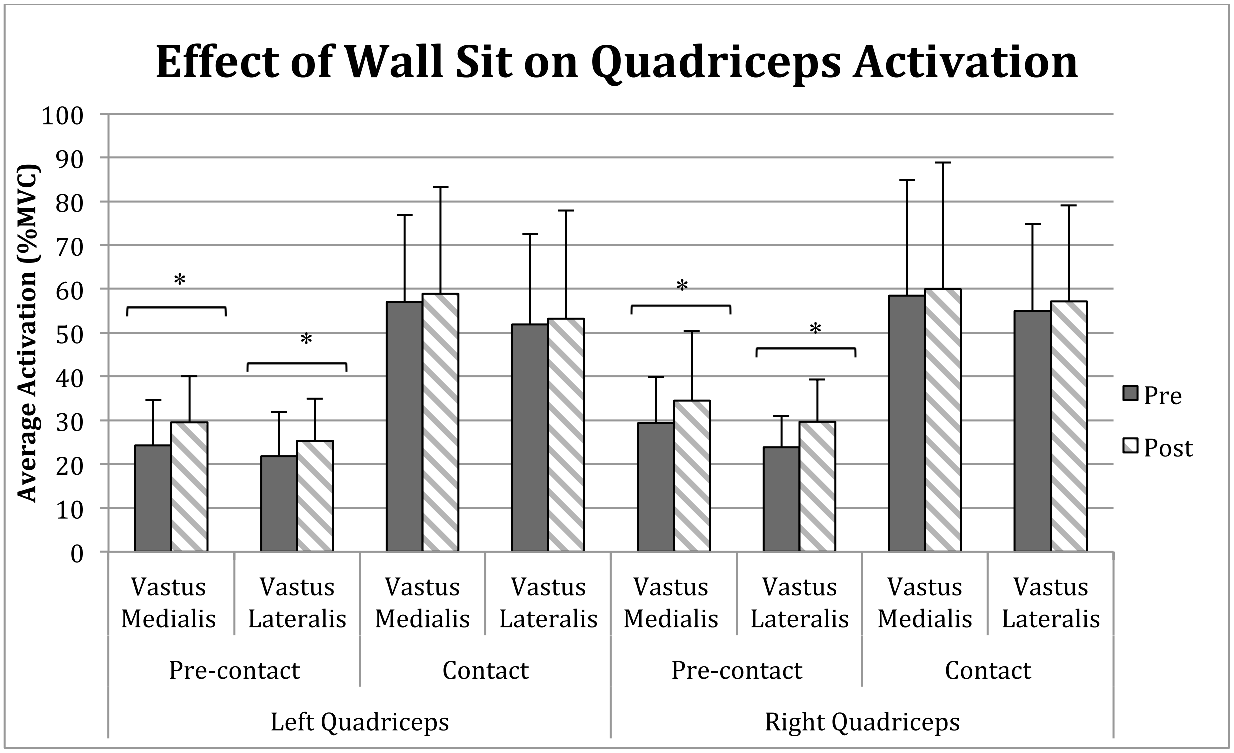

Figure 18. Effect of wall sit fatigue on quadriceps activation during the pre-contact and contact phase. Standard deviation bars shown.

4.2.3 Effect of Wall Sit Fatigue on Force

There was no significant effect of wall sit fatigue on impact peak force ($p = 0.91$), sustained push force ($p = 0.37$) or on standard deviation of the sustained push phase force ($p = 0.09$).

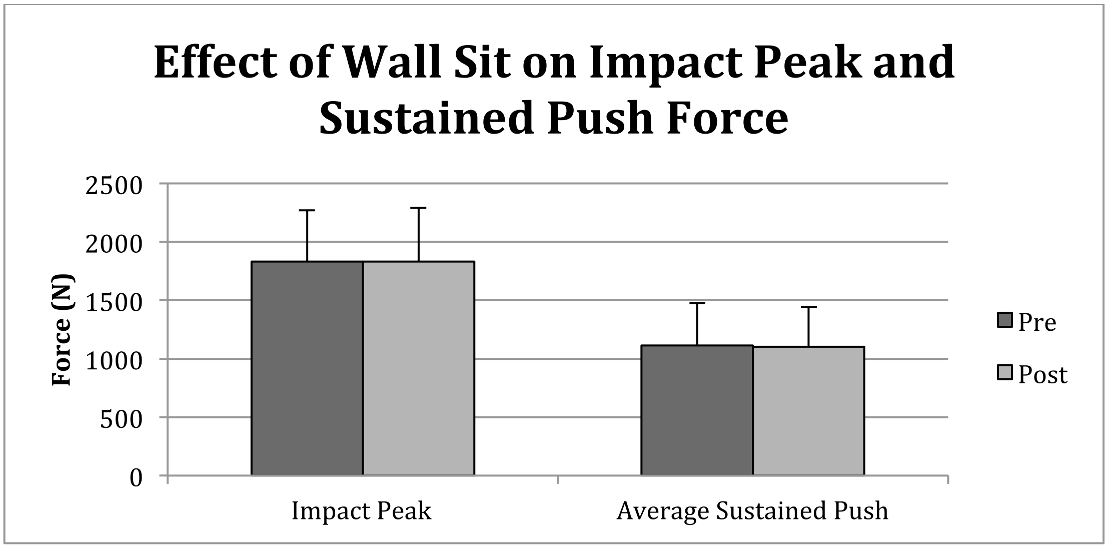

Figure 19. Effect of wall sit fatigue on impact peak and sustained push force. Standard deviation bars shown.

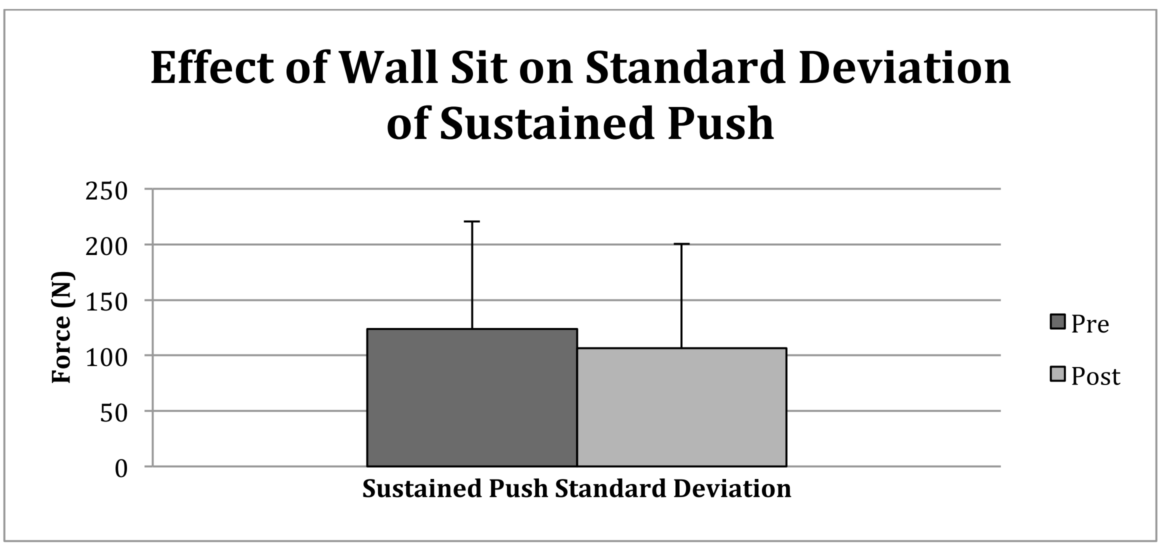

Figure 20. Effect of wall sit fatigue on standard deviation of sustained push force. Standard deviation bars shown.

4.2.4 Effect of Wall Sit on MdPF

There was a significant decrease is MdPF in all 4 muscles (Left VL: p = 0.0035, Left VM: p = 0.0004, Right VL: p = 0.0018, Right VM = 0.0060) between the start and end of the wall sit trial. In the left quadriceps, both the VL (Start: 70.4Hz (SD = 11.3); End: 62.5Hz (SD = 12.7)) and VM (Start: 69.6Hz (SD = 7.8); End: 64.2Hz (SD = 11.5)) decreased in MdPF over the course of the wall sit. Similarly, in the right quadriceps, both the VL (Start: 72.6Hz (SD= 13.7); End: 65.2Hz (SD = 11.5)) and VM (Start; 63.2Hz (SD = 4.2); 58.5Hz (SD = 7.0)) also decreased in MdPF over the course of the wall sit trial (Figure 21).

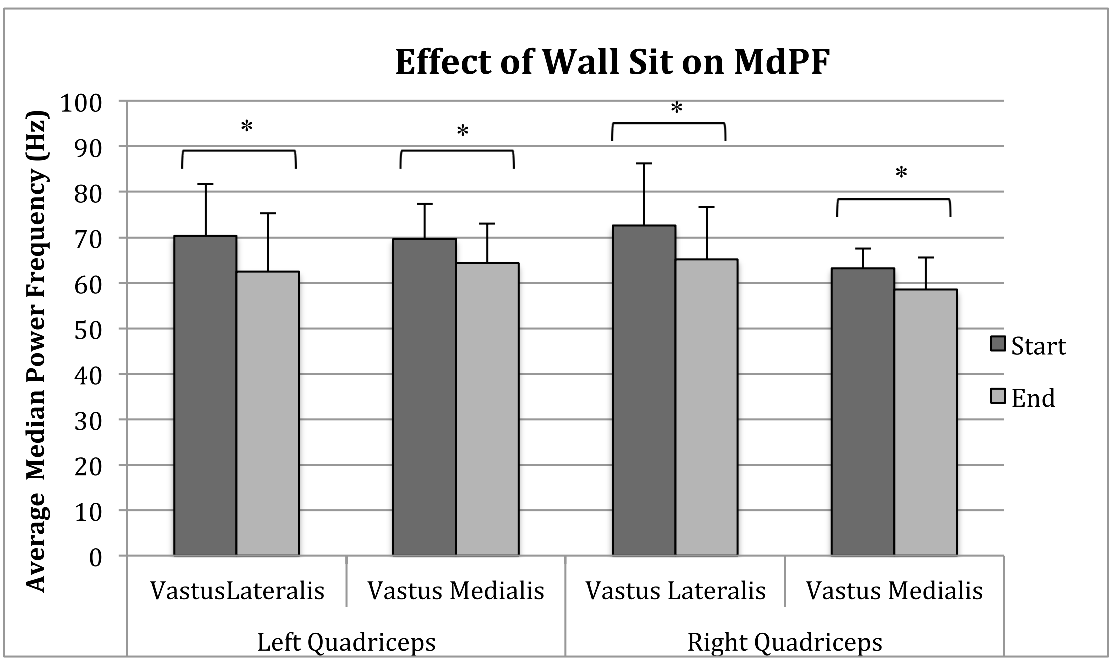

Figure 21: Wall sit MdPF. A decrease was found in all four quadriceps muscles measured.

4.3 Repetitive scrumming

4.3.1 Effect of Pre-Wall Sit Repetitive scrumming

4.3.1.1 Effect of Pre-Wall Sit Repetitive scrumming on Spine Angle

Prior to the wall sit, a significant effect of repetitive scrumming was found with respect to average angle in the cervical region of the spine during the pre-contact phase ($p = 0.0348$). Similar to wall sit fatigue, the average cervical angle became significantly less extended (First: $\bar{x}$ = -12.3°, SD = 15.1°; Last: $\bar{x}$ = -7.1°, SD = 13.7°) between the first and fifth pre-wall sit trials due to repetitive scrumming. No other significant changes occurred in the lumbar region (average: p = 0.43; maximum: p = 0.40; standard deviation: p = 0.69) thoracic region (average: p = 0.52; maximum: p = 0.47; standard deviation: p = 0.62) or the cervical region (maximum: p = 0.39; standard deviation: p = 0.56) due to repetitive scrumming in the pre-contact phase.

Additionally, prior to the wall sit in the contact phase, no significant changes occurred as a result of repetitive scrumming in the lumbar region (average: p = 0.11; maximum: p = 0.24; standard deviation: p = 0.95) thoracic region (average: p = 0.71; maximum: p = 0.32; standard deviation: p = 0.90) or the cervical region (average: p = 0.12; maximum: p = 0.08; standard deviation: p = 0.99).

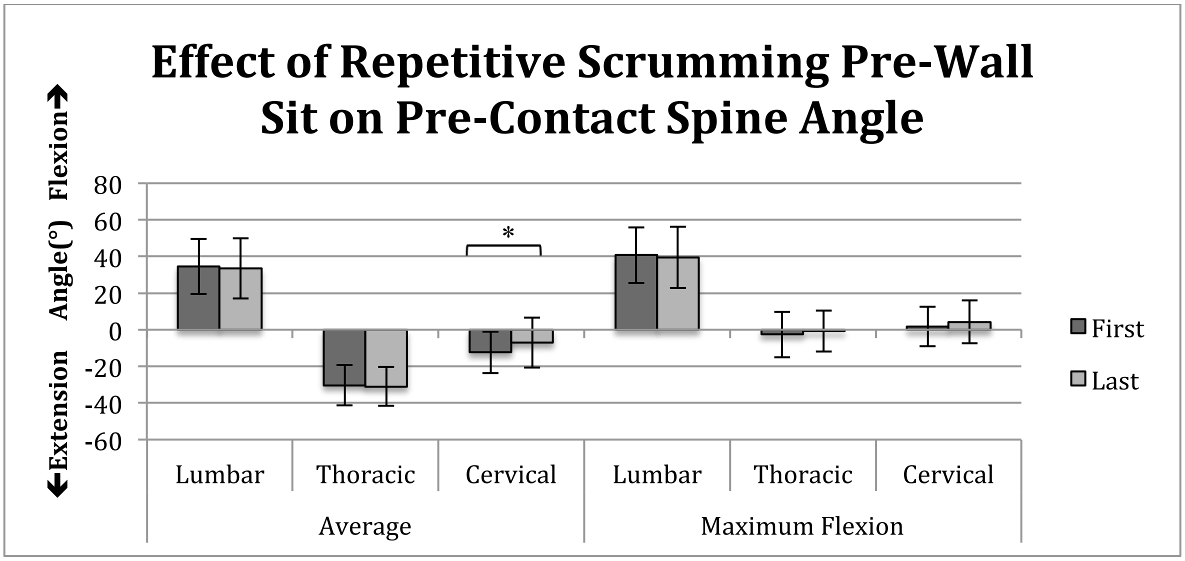

Figure 22. Effect of pre-wall sit repetitive scrumming on pre-contact spine angle. Standard deviation bars shown.

4.3.1.2 Effect of Pre-Wall Sit Repetitive scrumming on Muscle Activation

4.3.1.2.1 Effect of Pre-Wall Sit Repetitive scrumming on Trunk Activation

Prior to the wall sit, there was a significant effect of repetitive scrumming in both the left ($p = 0.0109$) and right ($p = 0.0005$) TES during the contact phase. Both the left (First: $\bar{x}$ = 55.4% MVC, SD = 47.9%; Last: $\bar{x}$ = 43.5% MVC, SD = 39.0%) and right (First: $\bar{x}$ = 55.4% MVC, SD = 31.0%; Last: $\bar{x}$ = 44.1% MVC, SD = 32.8%) average activation decreased between the first and fifth pre-wall sit trials. There was no significant effect of pre-wall sit repetitive scrumming on average activation in the left ($p = 0.54$) and right ($p = 0.23$) TES during the pre-contact phase.

Additionally, there was no significant effect of pre-wall sit repetitive scrumming on LES, EO or RA activity. During the pre-contact phase the left ($p = 0.73$) and right ($p = 0.28$) LES, the left ($p = 0.24$) and right ($p = 0.89$) EO and the left ($p = 0.39$) and right ($p = 0.26$) RA activity did not vary significantly. During the contact phase the left ($p = 0.05$)

and right (p = 0.08) LES, the left (p = 0.66) and right (p = 0.17) EO and the left (p = 0.16) and right (p = 0.86) RA activity did not vary significantly.

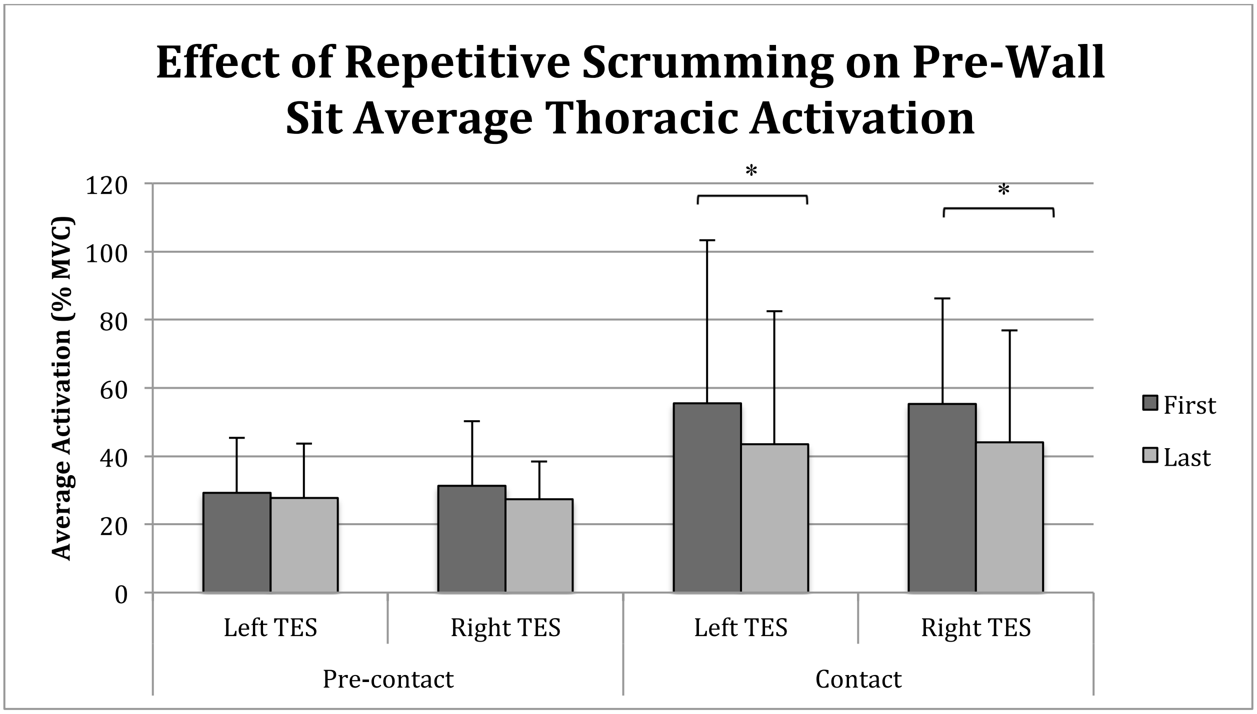

Figure 23. Effect of pre-wall sit repetitive scrumming on thoracic activation. Standard deviation bars shown.

4.3.1.2.2 Effect of Pre-Wall Sit Repetitive scrumming on Quadriceps Activation

Prior to the wall sit, there was a significant effect of repetitive scrumming on the right VM (p = 0.0013) during the pre-contact phase, and left VM (p = 0.0271) and left VL (p = 0.0473) during the contact phase. During the pre-contact phase the right VM decreased in average activation between the first and fifth trial (First: $\bar{x}$ = 30.8% MVC, SD = 11.8%; Last: $\bar{x}$ = 26.8% MVC, SD = 9.5%). During the contact phase the left VM (First: $\bar{x}$ = 61.6% MVC, SD = 25.4%; Last: $\bar{x}$ = 49.5% MVC, SD = 19.6%) and left VL (First: $\bar{x}$ = 57.3% MVC, SD = 24.5%; Last: $\bar{x}$ = 47.1% MVC, SD = 19.2%) both decreased in average activation due to repetitive scrumming. There was no significant difference in the left VL (p = 0.31), left VM (p = 0.99) and right VL (p = 0.10) during the pre-contact phase and right VM (p = 0.11) and right VL (p = 0.18) during the contact phase due to repetitive scrumming.

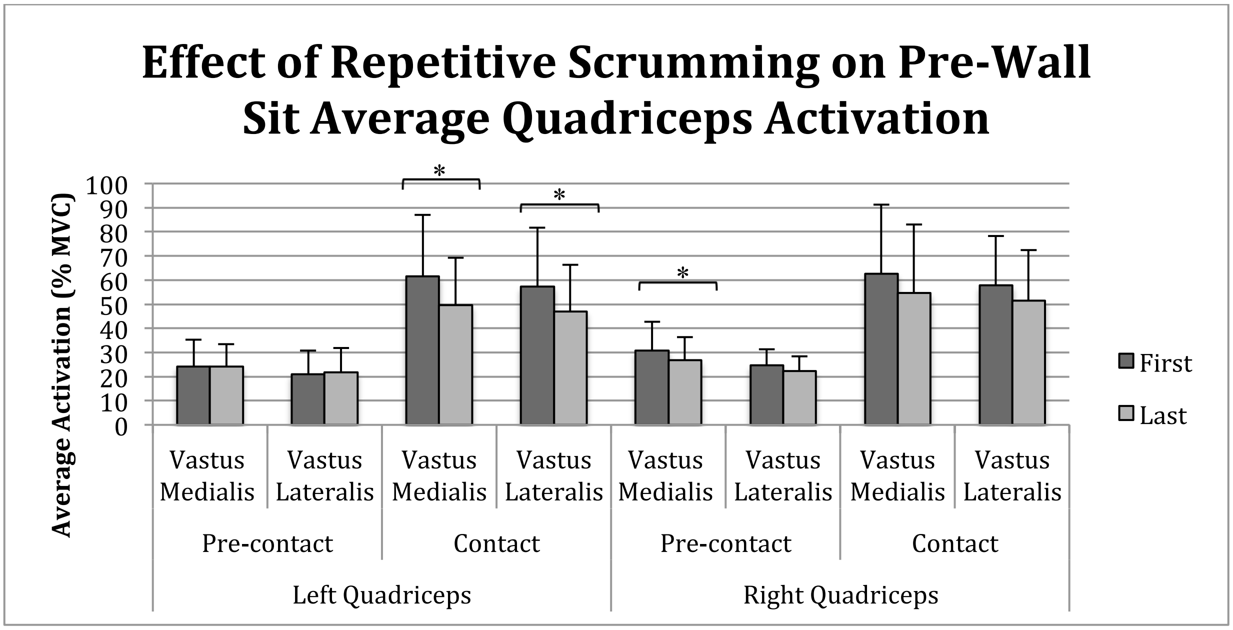

Figure 24. Effect of pre-wall sit repetitive scrumming on quadriceps activation. Standard deviation bars shown.

4.3.1.3 Effect of Pre-Wall Sit Repetitive scrumming on Force

Prior to the wall sit, there was no significant effect of repetitive scrumming on impact peak force (p = 0.94) sustained force (p = 0.08) or standard deviation of sustained force (p = 0.34).

4.3.2 Effect of Post-Wall Sit Repetitive scrumming

4.3.2.1. Effect of Post-Wall Sit Repetitive scrumming on Spine Angles

Following the wall sit, a significant effect was found for repetitive scrumming in the lumbar (p = 0.0088), thoracic (average: p = 0.0224; maximum flexion: p = 0.0058) and cervical (average: p = 0.0142; maximum flexion: p = 0.0048) regions during the contact phase. In the lumbar region, the standard deviation of the spine angle increased significantly between the first and fifth trial (First: $\bar{x}$ = 2.1°, SD = 1.0°; Last: $\bar{x}$ = 3.5°, SD = 1.4°). In the thoracic region both the average angle (First: $\bar{x}$ = -8.9°, SD = 12.1°; Last: $\bar{x}$ = -5.5°, SD = 11.6°) and the maximum flexion angle (First: $\bar{x}$ = 5.7°, SD = 10.1°; Last: $\bar{x}$ = 6.8°, SD = 10.3°) increased, or became significantly less extended due to repetitive scrumming. Similarly, in the cervical region, both the average angle (First: $\bar{x}$ = 30.0°, SD = 12.1°; Last: $\bar{x}$ = 33.8°, SD = 12.7°) and the maximum flexion angle (First: $\bar{x}$ = 33.9°, SD = 10.6°; Last: $\bar{x}$ = 37.7°, SD = 11.0°) increased, or became significantly more flexed due to repetitive scrumming. There was no significant effect of post-wall sit scrumming fatigue on lumbar average ($p = 0.60$) or maximum flexion ($p = 0.53$) angle during the contact phase. Similarly, there was no significant effect of post-wall sit repetitive scrumming on thoracic ($p = 0.09$) or cervical ($p = 0.49$) angle standard deviation during the contact phase.

Additionally, there was no significant effect of post-wall sit repetitive scrumming on lumbar (average: $p = 0.54$; maximum flexion: $p = 0.40$; standard deviation: $p = 0.45$), thoracic (average: $p = 0.35$; maximum flexion: $p = 0.60$; standard deviation: $p = 0.59$), or cervical (average: $p = 0.17$; maximum flexion: $p = 0.75$; standard deviation: $p = 0.30$) spine angles during the pre-contact phase.

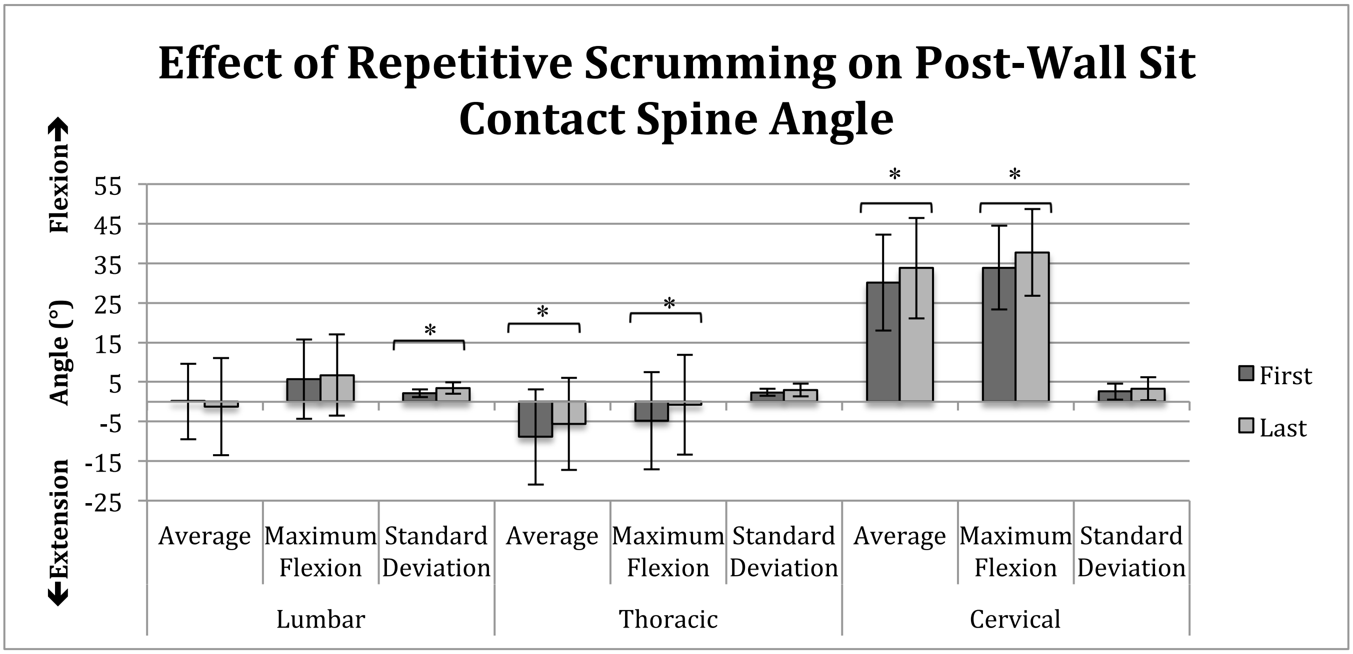

Figure 25. Effect of post-wall sit repetitive scrumming on contact spine angle. Standard deviation bars shown.

4.3.2.2 Effect of Post-wall Sit Repetitive Scrumming on Muscle Activation

4.3.2.2.1 Effect of Post-wall Sit Repetitive Scrumming on Trunk Activation

Following the wall sit, there was a significant effect of repetitive scrumming in both the left (p = 0.0462) and right (p = 0.0095) TES during the contact phase. Both the left (First: $\bar{x}$ = 51.0% MVC, SD = 43.0%; Last: $\bar{x}$ = 37.4% MVC, SD = 24.3%) and right (First: $\bar{x}$ = 48.7% MVC, SD = 31.9%; Last: $\bar{x}$ = 33.8% MVC, SD = 20.3%) average activation decreased between the first and fifth post-wall sit trials. There was no significant effect of post-wall sit repetitive scrumming on average activation in the left (p = 0.13) and right (p = 0.63) TES during the pre-contact phase.

Additionally, there was no significant effect of post-wall sit repetitive scrumming on LES, EO or RA activity. During the pre-contact phase the left (p = 0.20) and right (p =

0.84) LES, the left (p = 0.39) and right (p = 0.81) EO and the left (p = 0.33) and right (p = 0.09) RA activity did not vary significantly due to repetitive scrumming. During the contact phase, the left (p = 0.05) and right (p = 0.08) LES, the left (p = 0.66) and right (p = 0.17) EO and the left (p = 0.16) and right (p = 0.86) RA activity did not vary significantly due to repetitive scrumming.

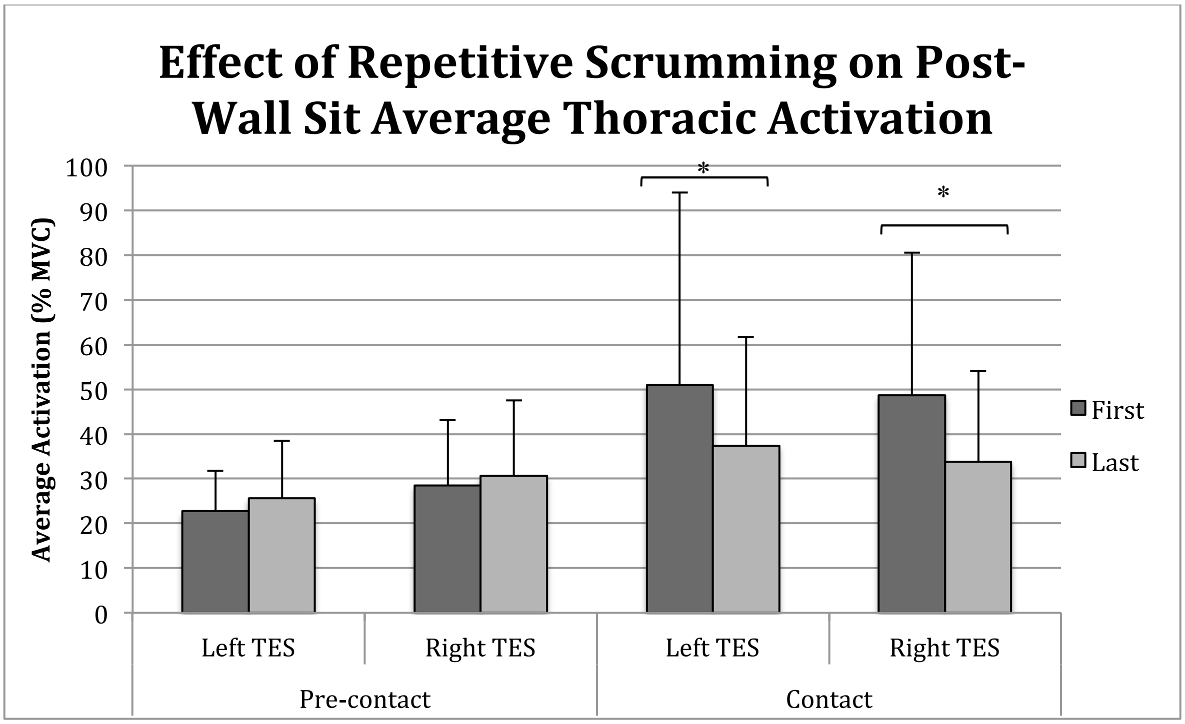

Figure 26. Effect of post-wall sit repetitive scrumming on thoracic activation. Standard deviation bars shown.

4.3.2.2.1 Effect of Post-wall Sit Repetitive Scrumming on Quadriceps Activation

Following the wall sit, there was a significant effect of repetitive scrumming leading to an increase in all quadriceps muscles during both phases. During the pre-contact phase, both the left VM (p = 0.0220; First: $\bar{x}$ = 26.1% MVC, SD = 9.2%; Last: $\bar{x}$ = 31.2% MVC, SD = 13.1%) and VL (p = 0.0070; First: $\bar{x}$ = 22.4% MVC, SD = 8.3%;

Last: $\bar{x}$ = 28.7% MVC, SD = 12.8%) as well as the right VM (p = 0.0037; First: $\bar{x}$ = 27.5% MVC, SD = 11.7%; Last: $\bar{x}$ = 34.2% MVC, SD = 17.2%) and VL (p = 0.0013; First: $\bar{x}$ = 25.0% MVC, SD = 7.8%; Last: $\bar{x}$ = 31.1% MVC, SD = 17.3%) all increased in activation between the first and fifth trial following the wall-sit. Similarly, during the contact phase, both the left VM (p = 0.0367; First: $\bar{x}$ = 53.5% MVC, SD = 20.1%; Last: $\bar{x}$ = 61.1% MVC, SD = 24.6%) and VL (p = 0.0419; First: $\bar{x}$ = 49.4% MVC, SD = 19.2%; Last: $\bar{x}$ = 58.0% MVC, SD = 23.8%) as well as the right VM (p = 0.0238; First: $\bar{x}$ = 53.5% MVC, SD = 26.8%; Last: $\bar{x}$ = 61.7% MVC, SD = 33.0%) and VL (p = 0.0213; First: $\bar{x}$ = 53.2% MVC, SD = 20.3%; Last: $\bar{x}$ = 61.3% MVC, SD = 25.6%) all increased in activation between the first and fifth trial following the wall-sit.

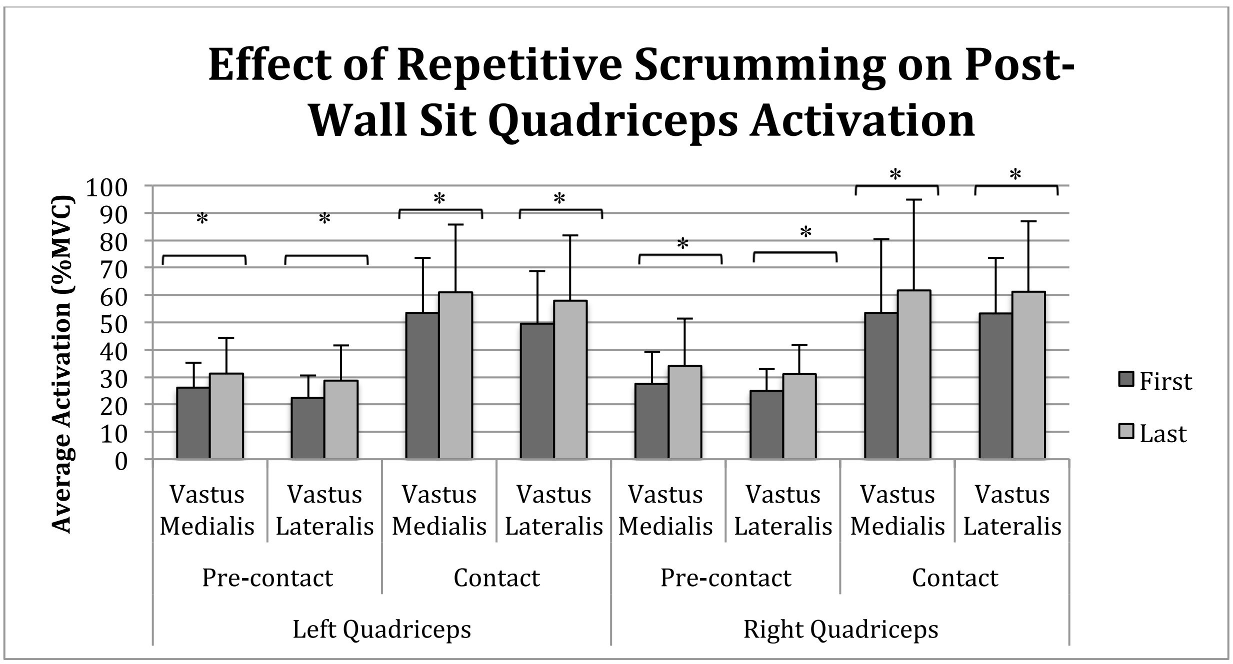

Figure 27. Effect of post-wall sit repetitive scrumming on quadriceps activation. Standard deviation bars shown.

4.3.1.3 Effect of Post-Wall Sit Repetitive Scrumming on Force

Following the wall sit, there was a significant effect of repetitive scrumming on the standard deviation of the sustained push force (p = 0.0404) such that the standard deviation increased (First: $\bar{x}$ = 83.1N, SD = 54.6N; Last: $\bar{x}$ = 138.9N, SD = 127.9N) between the first and fifth trials. There was no significant effect of repetitive scrumming on impact peak force (p = 0.06) or sustained force (p = 0.43).

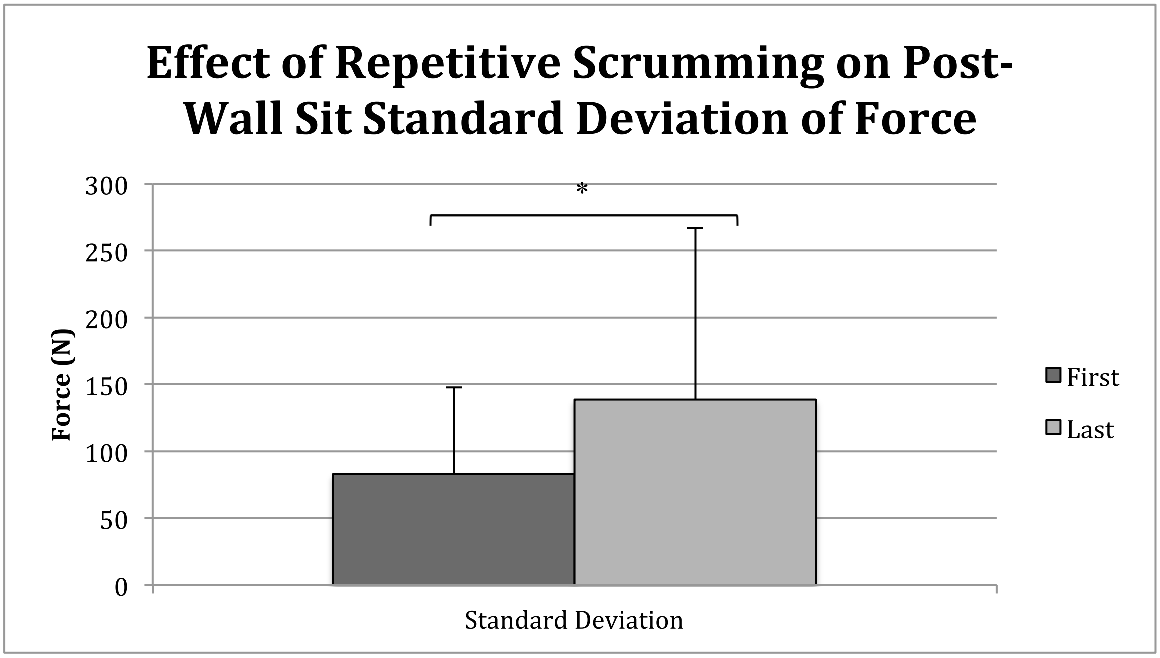

Figure 28. Effect of post-wall sit repetitive scrumming on standard deviation of sustained push force. Standard deviation bars shown.

4.4 Fatigue and Repetitive Scrumming Summary

Table 1. Significant findings across fatigue and repetitive scrumming conditions and Morel and Hautier (2016). ($p < 0.05$)

Condition	EMG Findings		Motion Findings		Force Findings
	Pre-Contact	Contact	Pre-Contact	Contact	Contact
Pre-Wall Sit Repetitive scrumming	-Decrease in right VM activation	-Decreased Activation of TES -Decrease in left quadriceps activation	-Increase in average cervical flexion		
Wall Sit Fatigue	-Increased activation of Quadriceps -Increased activation of LES	-Decreased activation of TES -Decreased activation of EO	-Increase in average/max cervical flexion -Increase in average/max lumbar extension	-Increase in average/max cervical flexion	
Post-wall Sit Repetitive scrumming	-Increased Quadriceps Activation	-Decreased activation of TES -Increased Activation of Quadriceps		-Increase in average/max cervical flexion -Increase in average/max thoracic flexion -Increase in lumbar angle standard deviation	-Increased standard deviation of sustained push phase
Morel and Hautier (2016)		-Decrease in ES activity -Decrease in left and right VL			-Increased standard deviation of sustained push phase

4.5 Hip Mobility

4.5.1 Relationship between Hip Flexion ROM and Impact Force

A moderate relationship between hip flexion ROM and impact force ($r = 0.55$; $p = 0.0290$) was observed, such that greater hip flexion ROM was related to greater impact force.

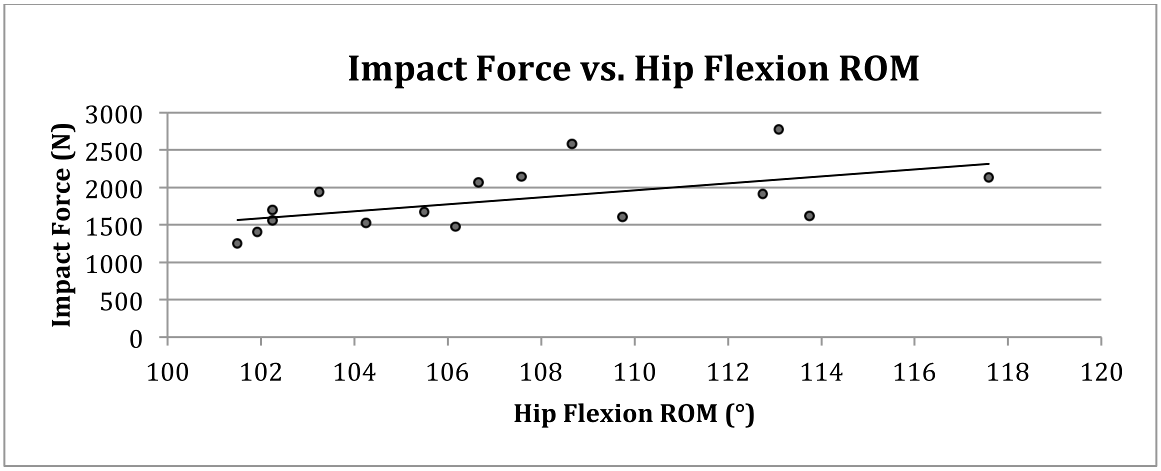

Figure 29. Relationship between hip flexion ROM and impact peak force (r = 0.54).

4.6 Lumbar Flexion

4.6.1 Relationship between Average Lumbar Flexion and Impact Force

A moderate relationship between average lumbar flexion and impact force ($r = 0.53$; $p = 0.0347$) was observed, such that as average lumbar flexion increased, impact force also increased.

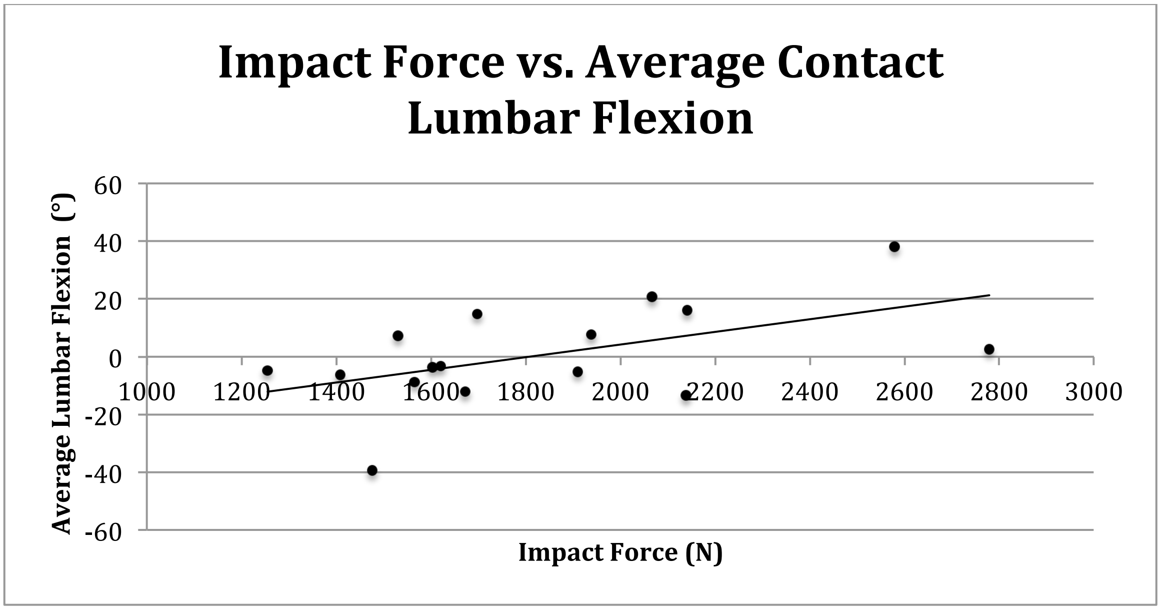

Figure 30. Relationship between average lumbar flexion and impact force (r = 0.53)

4.7 BMI

4.7.1 Relationship between BMI and Sustained Force

A moderate relationship between BMI and sustained force (r = 0.53; p = 0.0325) was observed, such that as BMI increased, sustained force also increased.

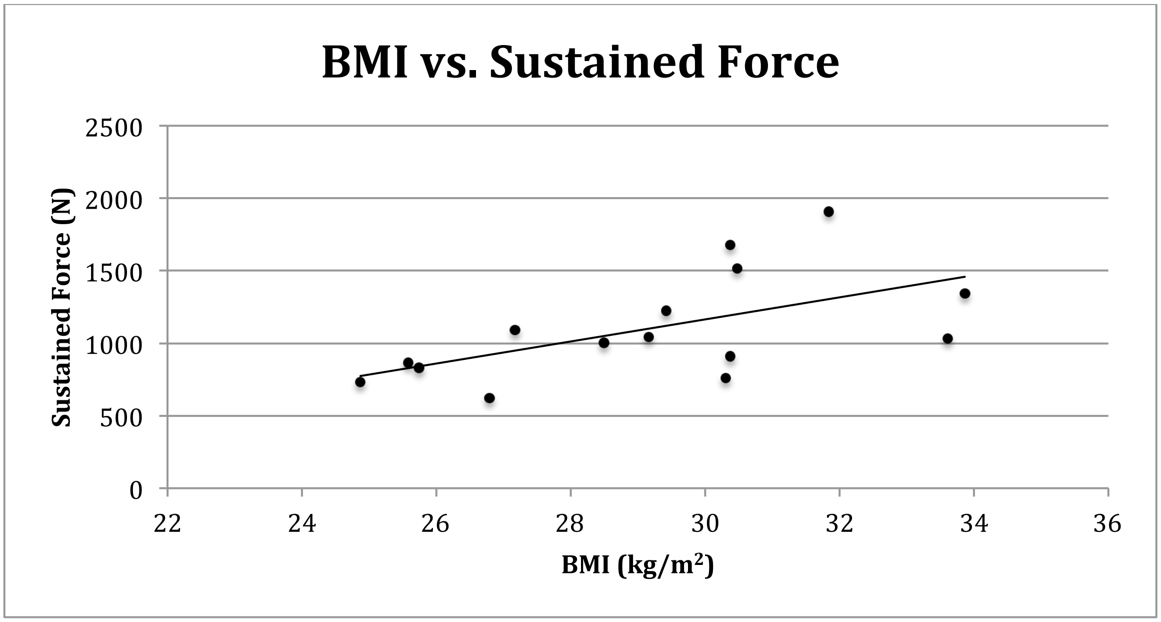

Figure 31. Relationship between BMI and sustained force (r = 0.53)

4.8 Wall Sit Duration

4.8.1 Relationship between Wall Sit Duration and Impact Force

A moderate relationship between wall sit duration and pre-wall sit impact force ($r = 0.52$; $p = 0.0376$) was observed, such that as wall sit duration increased, pre-wall sit impact force also increased.

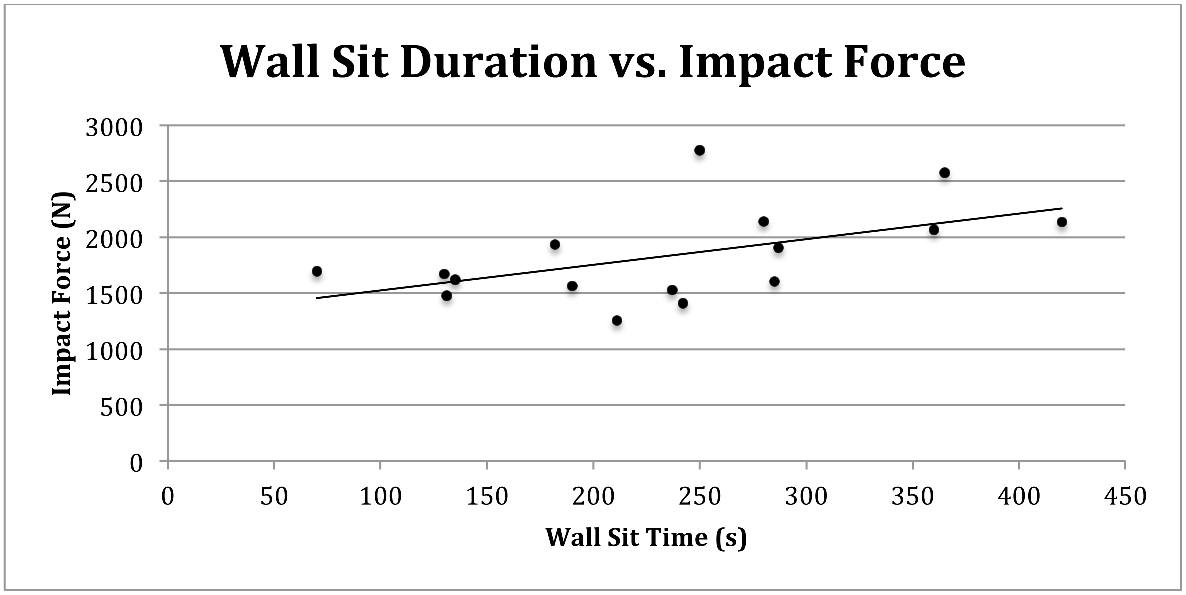

Figure 32. Relationship between wall sit duration and impact force (r = 0.52)

4.8.2 Relationship between Wall Sit Duration and Sustained Force

A moderate relationship between wall sit duration and pre-wall sit sustained force ($r = 0.54$; $p = 0.0376$) was observed, such that as wall sit duration increased, pre-wall sit sustained force also increased.

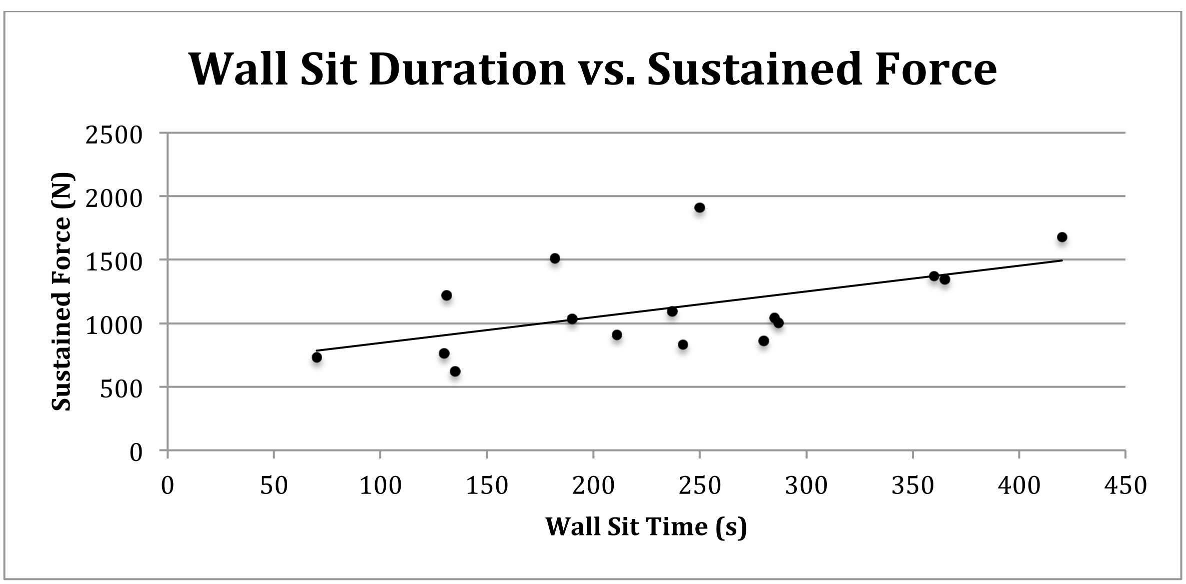

Figure 33. Relationship between wall sit duration and sustained force (r = 0.54)

5. Discussion

5.1. Revisiting the Purpose

The purpose of this study was to examine a fatiguing protocol of the knee extensors during a simulated individual rugby scrum in order to determine the influence of muscular fatigue on spinal posture, muscle activation and force output. Further, the correlation of hip mobility to spinal posture and force output was conducted to determine the effect of sagittal hip mobility on the rugby scrum. Lastly, anthropometrics and performance measures were examined for their influence on spine posture and force output.

5.1.1 Revisiting the Hypotheses

It was hypothesized that spinal flexion would become more prominent and force output would decrease following fatigue. Spine flexion did increase following fatigue, predominantly in the cervical region; however, both sustained force and impact peak did not vary significantly. It was also hypothesized that a reduced level of sagittal hip mobility would result in a greater degree of spinal flexion and decreased force output during simulated scrumming. Impact peak force was positively related to sagittal hip mobility, however, spinal flexion was unrelated to hip mobility.

5.2 Fatigue

5.2.1 Mechanism of Fatigue

Though rugby is considered to be a demanding sport (Deutsch et al., 2007; Roberts et al., 2010) the influence of fatigue on rugby scrum biomechanics is largely unexplored. From an epidemiology perspective, Taylor, Kemp, Trewatha, and Stokes (2014) determined that the rate of injury from a reset scrum (a scrum that must be redone) was 1.6 times greater then a first set scrum. Therefore, acute fatigue could influence rugby scrumming biomechanics in a way that predisposes individuals to a greater risk of injury.

Morel and Hautier (2016) recently looked at the role of repetitive scrumming (6s trials every 30s) during the contact phase to determine the influence of repetitive scrumming on EMG of the VL and ES. They assumed that any changes they observed were attributable to fatigue, as maximal voluntary and maximal evoked force output of the quadriceps decreased over the course of the 6 trials. Though the changes are likely related to fatigue, they may also be due to a learning or practice effect. Therefore, the current study will refer to changes between the first and fifth trial as the effect of repetitive scrumming. Morel and Hautier (2016) found a decrease in activation in both the VL and ES between the first and sixth trials as well as an increase in standard deviation of the sustained push. To their surprise, they did not find a decrease in peak impact force or average sustained force. Given that the knee extensors are a key group contributing to force production (Quarrie & Wilson, 2000), they attributed this change to fatigue as a result of maximal isometric contractions in the quadriceps. They suggested that this resulted in decreased intrinsic muscle force attributable decreased blood flow, though they did not speak to the overall compensatory mechanism that individuals use to maintain scrum force with a decrease in quadriceps force. They postulated that the decrease in the ES muscle activation was due to central fatigue. The current study puts this into question given that there was no significant decrease in activation in any other trunk muscle besides the ES following repetitive scrumming. It is plausible there is there is a specific central fatigue effect on the ES musculature following fatigue of the quadriceps (Hart et al., 2006) but also plausible that the ES is also specifically fatigued following repetitive rugby scrumming.

5.2.2 Repetitive Scrumming and Wall Sit Fatigue

Following the wall sit, the current study found some similarities in the effect of repetitive scrumming to Morel and Hautier (2016) such as an increase of standard deviation of sustained force, a decrease in ES activation and no significant differences in impact peak force or sustained push force. However, the current study found an increase in all quadriceps muscle activation across both phases, rather than the decrease observed by Morel and Hautier (2016). This increase in quadriceps activation was similar to findings in the pre-contact phase following wall sit fatigue, and therefore the increase in activation may be attributable to the maximal wall sit to fatigue performed moments earlier. Following wall sit fatigue, the LES activation also increased, in combination with an increase in lumbar extension but each of these differences were non-significant in the contact phase. Spine motion, which was not collected by Morel and Hautier (2016), revealed increased cervical and thoracic maximum and average flexion, as well as increased standard deviation of lumbar spine angle. The wall-sit induced fatigue demonstrated similar effects resulting in a decrease in TES activation and an increase in cervical flexion during the contact phase. This is important as an increase in flexion is a key mechanism of spine injury (Wade et al., 2014; Weinhoffer et al., 1995) especially in combination with high compression forces (Callaghan & McGill, 2001; Dolan & Adams, 1998) as are found in the rugby scrum.

Prior to the wall sit, the only significant effect of repetitive scrumming was a decrease in contact TES activation and left quadriceps activation and an increase in cervical flexion pre-contact. The decrease in the left quadriceps activation supports the previous notion that, in the absence of the wall sit, the activation levels of the quadriceps decreases due to repetitive scrumming (Morel & Hautier, 2016; Morel, Rouffet, Bishop, Rota, & Hautier, 2015). There may be only minor fatigue occurring in the pre-wall sit trials owed to the low work-to-rest ratio (1:18) compared to those performed by Morel and Hautier (2016) (1:5). Nonetheless, the effects of fatigue appear to be present given the similarity of the output measures to the other two conditions, which must be taken into consideration given that a common method of observing individual scrumming is 5s trial with 1-2 minute rests (Cazzola et al., 2015; Swaminathan, Williams, Jones, & Theobald, 2015).

5.2.3 Considerations regarding Fatigue

It appears that fatigue, whether induced by repetitive scrumming or performing a wall sit to failure, leads to an increase in cervical flexion and a decrease in TES activation with no significant effect on impact peak or sustained force production as demonstrated by the current study and Morel and Hautier (2016). This could be due to a variety of factors.

First, it could be attributed to kinematic factors. As previously stated, the knee extensors are essential for force production in the rugby scrum (Quarrie & Wilson, 2000). Fatigue of the quadriceps has been shown lead to an increased extension at knee (Thomas, McLean, & Palmieri-Smith, 2010) and hip (Augustsson et al., 2006) during athletic tasks. Additionally, the average knee flexion angle, in the absence of fatigue during the sustained phase in the rugby scrum, has been measured at 101.18° (Wen-Lan, 2005) and 107° (Quarrie & Wilson, 2000), however, the maximum torque angle of the knee is approximately 130° (Haffajee, Moritz, & Svantesson, 1972). Therefore, in order to compensate for fatigue and decreased force of the quadriceps, individuals may become more extended in the lower limb, approaching the maximum scrum force production knee angle proposed by Hislop (1982) of 115-125°. This is supported by other findings that individuals produce their greatest force while scrumming in a “lower limb extended” position and that a greater angle at the hip leads to higher scrum force production (Quarrie & Wilson, 2000).

As a result of this possible extension in the hip and knee, and in order to maintain an angle at the ankle to allow adequate friction of the cleats (Swaminathan et al., 2015), the participants’ centre of mass was likely at a higher position following fatigue. However, in order to contact the scrum machine axially in the same way, it would require compensation higher up the kinetic chain to lower the shoulders to same height, specifically increased cervical flexion. Admittedly, cervical flexion may not solely flex the spine sufficiently to lower the shoulder position, but it may be in conjunction with flexion of the upper thoracic spine, as flexion of the cervical region has been highly correlated to flexion of the upper thoracic region (Tsang, Szeto, & Lee, 2013). This may have been missed following wall sit fatigue in the current study given that the full thoracic region was measured, however, the whole thoracic region did show a statistically significant increase in flexion in post-wall sit repetitive scrumming.

A second explanation, though perhaps in conjunction with the first, can be attributed to muscle activation. Increased activity of the paraspinal muscles has been to shown to increase spinal compression, thereby stabilizing the core (Adams & Hutton, 1982). Gregory et al. (2008) found an increase in spinal flexion and a decrease in EO activation and the left TES muscle activity following a quadriceps-fatiguing task in a firefighting population. They attributed this decrease in activation to decreased co-contraction of the trunk muscles following fatigue due to the energetic cost of co-contraction. Therefore, it is plausible that decreased activation of the EO and TES following wall sit fatigue was due to decreased co-contraction and stabilization of the trunk and may have resulted in increased cervical spine flexion.

A third possibility, again possibly in conjunction with the first two, is that each of the fatiguing tasks directly fatigued the TES while only the wall sit directly fatigued the EO. Direct fatigue, measured through decreased oxygenation of the ES during a lifting task, has been shown to increase spinal flexion in a lifting task (Mehta, Lavender, & Jagacinski, 2014). It is not difficult to imagine repetitive scrumming directly fatiguing the TES (Morel & Hautier, 2016) given the high forces being transduced through the spine while scrumming (Milburn, 1990; Preatoni et al., 2013; Quarrie & Wilson, 2000). However, during the wall sit, the TES and EO may play an important role in co-contraction in order to maintain a stable posture against the wall, resulting in fatigue. If that were the case, decreased oxidation through direct fatigue of the TES and EO in the wall sit, and solely the TES in repetitive scrumming, may be responsible for the increased cervical flexion observed during fatigue.

Another explanation, as put forth by Morel and Hautier (2016) is that the quadriceps are the primary musculature implicated in repetitive scrumming and wall sit fatigue (Appendix B), and the ES decrease in activation is attributable to central fatigue.

If this were the case then likely we would also expect to see decreases across the whole musculature of the trunk, which was not observed in this study. Perhaps this could be attributable to specific association of the ES and the quadriceps, which has been observed in literature (Hart et al., 2006). However, the activation of the LES increased during the pre-contact phase following wall sit fatigue, and was statistically insignificant during the contact phase. This explanation is not supported by the current study unless there is a direct central fatigue effect that acts solely on the TES as a result of quadriceps fatigue.

Finally, there may be no relationship between muscle activation and cervical flexion. Cazzola et al. (2015) showed that the LES was significantly less active (~60%) in machine scrumming than live scrumming and concluded that machine scrumming was much less taxing on the cervical region based on decreased activation of the sternocleidomastoid and upper trapezius. Therefore, using the same line of argumentation suggested by Gregory et al. (2008), contraction of the cervical extensor muscles may not have been prioritized due to metabolic demand elsewhere (fatigue of the quadriceps), leading to flexion in the cervical region due to a lack of necessity for extension or stabilization in that region.

5.2.4 Sustained and Impact Force Following Fatigue and Repetitive Scrumming

Perhaps the most significant finding in this study was that the participants were able to maintain their impact peak and sustained push force output in spite of the fatigue experienced in the wall sit and repetitive scrumming. Though a decrease in force output has been observed in other studies (Jougla et al., 2010; Morel, Rouffet, Bishop, Rota, & Hautier, 2015) and it is unlikely that rugby players could sustain their force output under any threshold of fatigue, it remains important that physiological markers of fatigue were present and yet no performance decrease was observed. This was may be attributable to the aforementioned extension in the lower limb (Quarrie & Wilson, 2000), approaching the maximum knee torque angle (Haffajee et al., 1972) and maximum scrumming angle (Hislop, 1982). It may also be attributable to factors not measured in the current study, such as an increase in activation of the hip extensors, such as the gluteus maximus. Regardless, it is clear that at the level of fatigue observed in the current study, rugby players were able to employ a compensatory strategy to maintain force output.

5.2.5 Standard Deviation of Force and Lumbar Spine Angle

Following the wall sit, repetitive scrumming resulted in an increased standard deviation of sustained force, which coincided with an increased standard deviation of the lumbar spine angle. This was the only of the three fatigue conditions where these two variables were significantly different as an effect of fatigue. The finding that the standard deviation of the sustained force increased has been found previously in literature (Morel and Hautier, 2016) and it has been suggested that this may lead to a reduced stability of the scrum (Cazzola et al., 2015) which has been extensively cited as source of collapse and cervical injury (Bohu et al., 2009; Dennison, Macri, & Cripton, 2012; Fuller et al., 2007; Kuster, Gibson, Abboud, & Drew, 2012; Milburn, 1990). Though there is no direct link between these two variables, it seems feasible that, in a kinetic chain movement such as the rugby scrum, an increased lumbar angle variability may lead to increased sustained force variability. An increased lumbar angle variability may also be a mechanism of injury, as repeated flexion and extension is used to induce disc herniation in animal models (Callaghan & McGill, 2001) However, it was beyond the scope of the current study to determine if the degree or frequency of flexion/extension is sufficient to induce herniation or any other spine injury.

5.3. The Influence of Hip Mobility

There was no significant relationship between any of the output variables and measures of hip extension mobility. This is perhaps unsurprising given that the hip remains in a flexed position throughout both the pre-contact and contact phases of rugby scrumming. It may be more surprising, and contrary to the hypothesis of this study, that there was very little influence of hip *flexion* mobility given the previously observed influence of reduced hip mobility on spinal flexion in lifting and athletic tasks (Dolan & Adams, 1993; Kim et al., 2014). However, this may be due to the low degree of hip ROM utilized during rugby scrumming. Wen-Lan (2005) found an average hip angle of 121.33° (59° of flexion) and Quarrie and Wilson (2000) found an average hip angle of 123.24° (57° of flexion) during scrumming. Given that all participant's maximum hip flexion ROM was between 100°-120° flexion in the current study, this unlikely to be approaching any of their end ROM.

5.3.1 The Relationship between Hip Flexion ROM and Impact Peak

There was a positive relationship between hip flexion ROM and impact peak, such that the individuals with the greatest hip flexion ROM also had the greatest impact peak force. Though participants appear to only attain around 58° of flexion in the contact phase of scrumming (Wen-Lan, 2005; Quarrie & Wilson, 2000), during the pre-contact phase in preparation for impact it appears as though they are more flexed at the hips (Appendix F). Therefore, it may be possible that participants with a greater degree of hip flexion ROM are able to achieve a more flexed hip in this position. This would give them a greater distance to accelerate during hip extension as they impact the scrum machine. However, during the contact phase where the hip is not maximally flexed, no relationship with sustained force was found.

5.4 Lumbar Spine Flexion and Impact Peak

There was a positive relationship between lumbar spine flexion during scrumming and impact peak, such that individuals that had the greatest degree of lumbar spine flexion during contact also had the highest impact peak. This may occur for the similar reason suggested for a greater degree of hip flexion ROM having positive relationship with impact peak force. A high degree of flexion (90-120 degrees) at the hip has been shown been shown to be contributed roughly equally by flexion of hip complex and the lumbar spine (Porter & Wilkinson, 1997). Though the hip does not appear to use a great deal of it's ROM during the contact phase, the lumbar spine does (> 88% of flexion ROM) (Swaminathan et al., 2016). Given that lumbar flexion angle was taken as an absolute value and not a percentage of maximum ROM, those with more flexible lumbar spines might be able to achieve a greater degree of flexion, particularly during the crouch phase in preparation for impact. Therefore, during the extension of the hips in preparation for impact of the scrum machine they would have a longer distance to create hip extension and generate acceleration and may therefore lead to a greater impact force.

5.5 The relationship between Mass, BMI and Force Output

Comparisons of pack masses are often presented on televised games with the heavier packs assumed to have an advantage. Contrary to expectations, there was no significant relationship between body mass and any force output variable, though this relationship has been suggested in literature (Quarrie & Wilson, 2000). There was, however, a positive relationship between BMI and sustained push force, such those with a higher BMI produced an increased sustained force. Props and Hookers are also known to have the highest degree of endomorphic somatotype (Holway & Garavaglia, 2009; Quarrie et al., 2002) and the greatest degree of adiposity (Holway & Garavaglia, 2009) as well as force output (Quarrie & Wilson, 2000). Endomorphy has also been shown have positive relationship with increased force production (Quarrie & Wilson, 2000), therefore, it is plausible to think that BMI might be related to increased force production.

5.6 The Relationship Between Wall Sit Duration and Impact Peak and Sustained Force

There was a significant relationship between wall sit duration and both impact peak force and sustained push force prior to the wall sit, such that those with the greatest wall sit time produced the greatest impact peak and sustained push force. Though previous research has linked cycle ergometer power to sustained push force output, maximal isometric force of lower limb extension did not have a significant relationship to force output (Quarrie & Wilson, 2000). There has been very limited research to the relationship between strength and power tests and the relationship with scrumming force. Therefore, an isometric muscular endurance test, such as the wall sit, may be a better predictor of force performance in the rugby scrum than a maximal isometric peak force test, perhaps due to the repetitive and frequent nature of scrumming.

5.7 Considerations and Future Directions

5.7.1 Considerations

There are a number of considerations regarding the current study: Though individual rugby scrums are extensively common in rugby research (Cazzola et al., 2015; Jougla et al., 2010; Milburn, 1990; Morel & Hautier, 2016; Quarrie & Wilson, 2000) it must be taken into account that the forces, muscle activation and body positions may not be akin to those found in live, full pack scrums. For example, Cazzola et al. (2015) found that the LES was approximately 60% more active in live scrumming, and therefore machine scrumming may not replicate live scrumming. However, Swaminathan et al. (2016) did find similar spine kinematics in machine and live scrumming and, given how commonly scrum machines are used in training, there may be merit to examining them as their own entity.

Further, the current scrum machine was constructed by the researchers to be counter-weighted and transportable in order to collect data in the laboratory. Though care was taken to make the dimensions, turf and pads as similar commercially built scrum machines as possible, there is the potential that some of the variation from the literature data is attributable to the scrum machine. However, the forces (Morel & Hautier, 2016; Quarrie & Wilson, 2000; Wen-Lan, 2005) activity of the LES (Cazzola et al., 2015) and the spine kinematics (Swaminathan et al., 2016) were all in very similar ranges to those reported in literature.

Another consideration with regards to the scrum machine is that a uniaxial force transducer was used to measure axial compression force. Though off axis forces are generally considered less critical for performance and usually represent instability and inefficiency of the scrum (Preatoni et al., 2013; Trewartha et al., 2014), it is possible that changes in these forces did occur and may have been influenced by the variables of interest.

Additionally, due to the number of available participants and the physical characteristics, such as increased adipose tissue, that makes collecting EMG data from front row participants difficult (Cazzola et al., 2015), it was not feasible collect only front row players. Though each individual collected in the study had at least 4 years of experience in the rugby scrum, and individuals tend to all assume a roughly similar body position in the scrum, those who play in the front row likely have had more experience directly contacting scrum machines. This may have influenced the results somewhat and must be taken into consideration for the current study. However, there are other scrum studies that have included participants outside the front row that would have similarly had to contend with this issue (Green, Kerr, Dafkin, & McKinon, 2015; Jougla et al., 2010; Quarrie & Wilson, 2000).

Another consideration was the role of fatigue attributable to the wall sit. Though each of the quadriceps showed a substantial decrease in MdPF ($p < 0.006$), it must be noted that this was taken across all participants, and therefore, there may have been individuals who experienced a much higher or lower degree of fatigue than their counterparts. Given that all participants were treated as though they were fatigued this may have influenced the results slightly.

Lastly, though the EMG and motion data were synchronized in this study, it was impossible to synchronize the force data with these two output measures, therefore, force values were established over a different visual inspection window. In order to determine the impact of the scrum machine, an accelerometer was affixed to the scrum pad section of the scrum machine, in order to clearly indicate the bind, impact and release of the scrum machine in the motion and EMG data. The pulse was also used to give approximations of the different components of the referee's cadence. Pulse and accelerometer data were both synchronized with EMG and motion data.

5.7.2 Future Directions

Given the lack of research that has examined rugby scrumming and its relationship to fatigue and hip mobility there are many areas that need to be further researched. In the area of fatigue, it is suggested that it might be beneficial to examine scrumming fatigue following a fatiguing protocol more realistic to rugby game simulation, such as the Bath University Rugby Shuttle Test, a test that requires many rugby specific movements such as shuttle running, rucking, mauling, scrumming, a lateral change of direction (Roberts et al., 2010). The resources and space required to complete the Bath University Rugby Shuttle Test made it infeasible to incorporate into the current study. Further, though the upper trapezius and sternocleidomastoid have been examined in rugby scrumming (Cazzola et al., 2015), examining these muscles as well as cervical extensors under fatigue may shed light onto the cervical flexion following fatigue observed in this study. Last, examining fatigue in the context of live scrumming would be crucial for determining the role of fatigue in match play.

Though hip mobility appeared to have little influence on spinal posture or force output in the current study, this may be due to the stability owed to machine scrumming, and perhaps a more significant influence would be found in the more unstable condition of live scrumming. Further, the current scrum apparatus was fixed, and therefore may not have challenged the hip complex to the same extent as if it were dynamic and the participant had to maintain proper scrum posture while moving. Last, the influence of hip mobility may be been compensated through a change in kinematics in the lower limb, however, lower limb kinematic data was not collected in the current study. Future studies should seek to determine the kinematic changes in the lower limb as well as testing other lower limb joints for ROM insufficiency given the closed kinetic chain nature of the rugby scrum.

5.7.3 Recommendations

Fatigue in individual machine scrumming appears to lead to a decrease in TES activation and an increase in cervical spine flexion with no decrease in force output. This is a potential mechanism of the high risk of cervical spine injury present in rugby players. Therefore, it is important for rugby players to have good muscular fatigue endurance in order to prevent fatigue and mitigate the associated injury risks. Further, it is important for coaches continue to substitute players early (in spite of the ability to maintain force production), as has been a recent trend in world rugby, in order to reduce the effects of fatigue in each individual. Given that this study was conducted against a scrum machine, it is also advisable that coaches are careful to avoid excessive fatigue in training where machine scrumming takes place. Hip mobility appears to play a very minor role in sustained push and therefore may not be a focus for coaches to improve scrumming performance. Lastly, a maximal wall sit to fatigue appears to have a positive relationship with both impact peak and sustained force and may therefore be a good test as an indicator of scrum force output ability.

6. Conclusion

The current study sought to determine the influence of fatigue and hip mobility on force output, spine motion and muscular activation. The data suggests that fatigue resulted in decreased activation of the TES and increased cervical flexion. Though the link between these two variables must still be explored, it may be attributable to lower limb extension resulting in a higher center of mass, direct fatigue of the TES, decreased co-contraction of the trunk, central fatigue or disuse of the cervical muscles in machine scrumming. Flexion of the cervical spine might be significant given the high rates of cervical spine injury in rugby players (particularly those who participate in the scrum) and that flexion under load is a known mechanism of cervical spine injury. Hip mobility appears to play little role in force output and spinal postures in the rugby scrum, with the exception of an increased impact peak, which may have some possible performance benefits. Last, the wall sit may be an effective fitness test for forwards given its relationship with impact force and sustained push performance in the scrum, but more work in this area would be required to validate this relationship.

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Appendix A

Pilot testing was undertaken to determine the influence of the wall sit on quadriceps extension force. Three active male participants were recruited (2 of which were athletes on the Wilfrid Laurier Varsity Rugby Team). Information regarding the participants is found in Table 3.

Table 2. Participant Information

Variable	Average (SD)
Age (years)	21.0 (± 3.0)
Height (m)	1.74 (± 0.07)
Mass (kg)	79.3 (± 13.3)
Wall sit time (s)	256.3 (± 59.3)
Dominant Leg	2 Right, 1 Left

Initially, participants came in and completed the screening questionnaire, which included information regarding their physical characteristics, activity level and injury information. Participants were excluded if they had any significant injuries that might influence their performance on either the wall sit or quadriceps extension.

They then performed a submaximal familiarization trial of quadriceps extensions on the cybex dynamometer (Figure A1). This involved 3 submaximal quadriceps extensions separated by 15 seconds rest. All quadriceps extensions involved a 50N pre-load, meaning the participant had to exceed 50N of force in order to start the trial. The familiarization trial was, therefore, critical to get familiar with this pushing threshold.

Figure A1. Quadriceps Extension on the Cybex dynamometer.
Retrieved from: http://www.isokinetic.info/

They then performed a maximal isometric pre-fatigue quadriceps extension. For all trials participants were instructed to consistently “ramp up” to their peak force. The trials could last up to 5 seconds but the participant was not required to push for that period of time and they usually achieved their maximum force around the midpoint of the trial. The quadriceps extensions were undertaken with the individual’s knee at an anatomical angle of 60° of flexion. All quadriceps extension testing was performed on the right quadriceps. Following the first maximal pre-fatigue quadriceps extension they were given 5 minutes to rest and then repeated with a second maximal quadriceps extension. The higher of these two peak force values was used as the pre-fatigue maximal force value.

The participants then completed a wall sit to fatigue. Similar to the study protocol they were instructed to sit against the wall with the knees and hips at a 90° angle until they are no longer able to maintain this posture (Wahl & Behm, 2008). The trial was finished if the participant deemed themselves unable to continue or was unable to maintain their posture near the 90° angle as visually determined by the researcher. Participants were allowed to readjust their position in order to return to the 90° angle throughout the trial to account for the poor friction of the foam surface they were against.

Following the wall sit participants were immediately returned to the cybex quadriceps extension dynamometer. Using the same protocol outlined for the pre-fatigue condition, they performed 10 maximum force exertions followed by a minute of passive rest for a total of 10 trials. Following this they were given 5 minutes of passive rest and then able to perform one final maximum contraction.

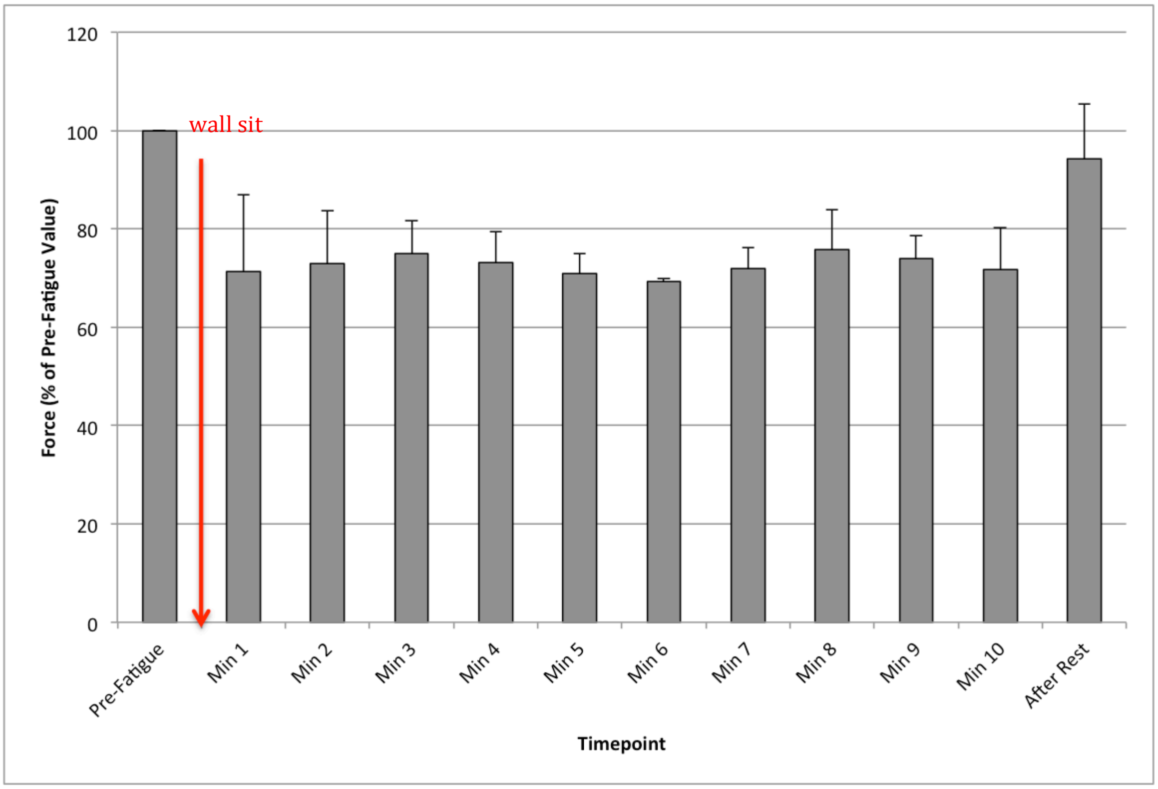

Figure A2. The influence of the wall sit on quadriceps extension force. Pre-fatigue = prior to wall sit, Min 1-10 = minutes that follow the wall sit, After rest = after 5 minutes of passive rest following the remainder of the trials. Standard deviation bars shown.

The wall sit resulted in a decreased force output that sustained for 10 minutes following fatigue. The force output values dropped to an average of 72% (SD = 2.0%) of the pre-fatigue peak output over the 10 minutes (min = 69%, max = 76%). Following 5 minutes of rest participants were able to return their force values to 94% (SD = 11%), nearly returning to baseline values. A summary of findings is included in figure A2.

This data revealed that the wall sit is a sufficient means of decreasing the extension force output of the quadriceps. It also shows that this fatigue is able to sustain for 10 minutes. Given that the post-fatigue protocol of the current study was a 90 second trial following the wall sit we can be confident that the quadriceps extensors were fatigued in the current study.

Appendix B

To confirm the presence of fatigue during the wall sit task, MdPF of quadriceps muscle EMG signal was examined. A decrease in MdPF has been known to occur as a result of fatigue in isometric contractions (Ament, Bonga, Hof, & Verkerke, 1996).

As outlined in section 3.3.1.1, EMG data were collected from the VM and VL of both the left and right legs. To avoid looking at the beginning of the trial where to participant was sometimes adjusting their position, or the end of the trial where participant may have been standing back up, the first 15 seconds and last 15 seconds were removed from the trial. Then, MdPF was determined for 10, 1-second long data periods, taken from both the start and the end of the trial. These were further averaged to get a 10 second MdPF average for both the start and end of the trial for each participant. Following this a related samples t-test was performed to determine if a difference existed between the start and end of each trial.

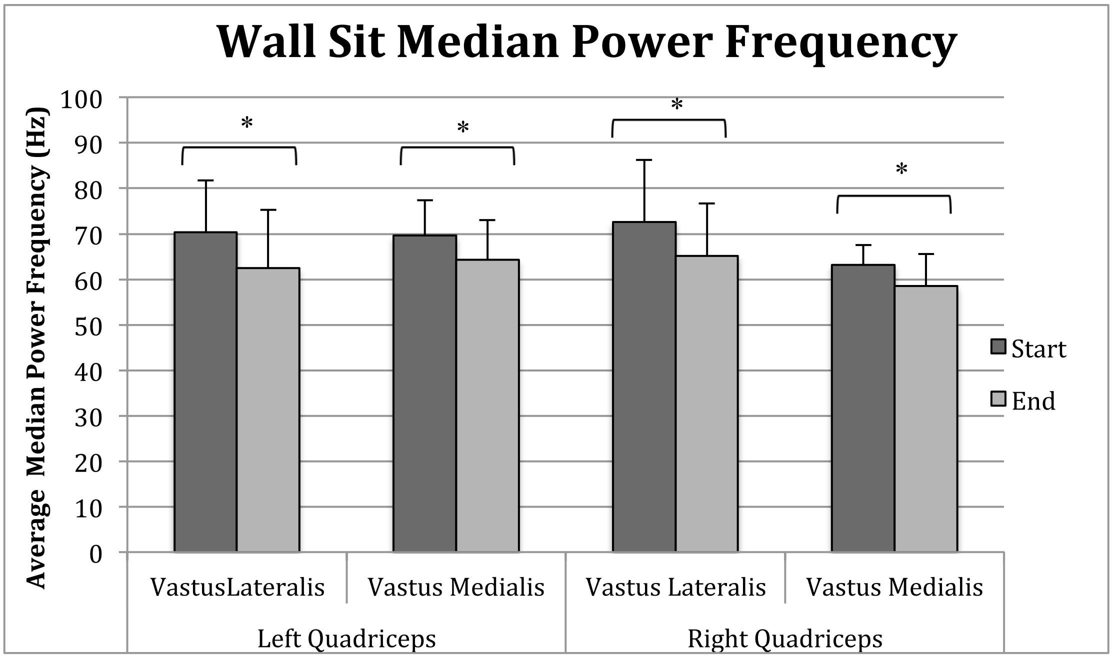

Figure B1: Wall sit MdPF. A decrease was found in all four quadriceps muscles measured.

There was a significant decrease is MdPF in all 4 muscles (Left VL: p = 0.0035, Left VM: p = 0.0004, Right VL: p = 0.0018, Right VM = 0.0060) between the start and end of the fatigue trial. In the left quadriceps, both the VL (Start: 70.4Hz (SD = 11.3); End: 62.5Hz (SD = 12.7)) and VM (Start: 69.6Hz (SD = 7.8); End: 64.2Hz (SD = 11.5)) decreased in MdPF over the course of the wall sit. Similarly, in the right quadriceps, both the VL (Start: 72.6Hz (SD = 13.7); End: 65.2Hz (SD = 11.5)) and VM (Start; 63.2Hz (SD = 4.2); 58.5Hz (SD = 7.0)) also decreased in MdPF (Figure B1).

We can therefore conclude that the wall sit was a sufficient stimulus to both decrease force output (appendix A) and cause muscular fatigue changes in the muscle (a decrease in MdPF).

Appendix C

Due to restrictions with the force measurement software (Logger Pro 3.9), the maximum sampling rate available for measurement was 250Hz when sampled for 90 seconds (the duration of the 5 post-fatigue trials). In order to determine if this sample rate was sufficient to capture the impact peak and sustained push, a pilot participant was recruited and performed a 15 second live trial at the maximum sampling rate (500Hz). Following this an FFT was constructed to observe the frequency content of the force data to ensure that a sampling rate of 250Hz was sufficient to capture the force frequency content.

Sampling was observed from approximately 2s prior to impact to the end of the trial and yielded the following FFT data (Figure C1).

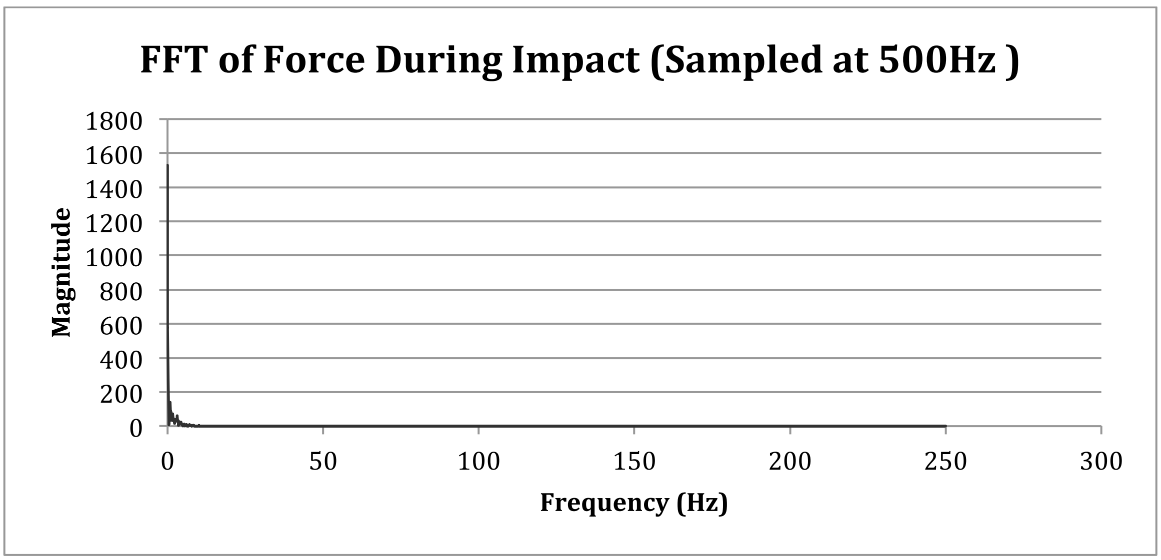

Figure C1. FFT of Force during impact sampled at 500Hz.

In order to gain a better resolution of the lower magnitude data, the scale was changed to 0-200 (Figure C2).

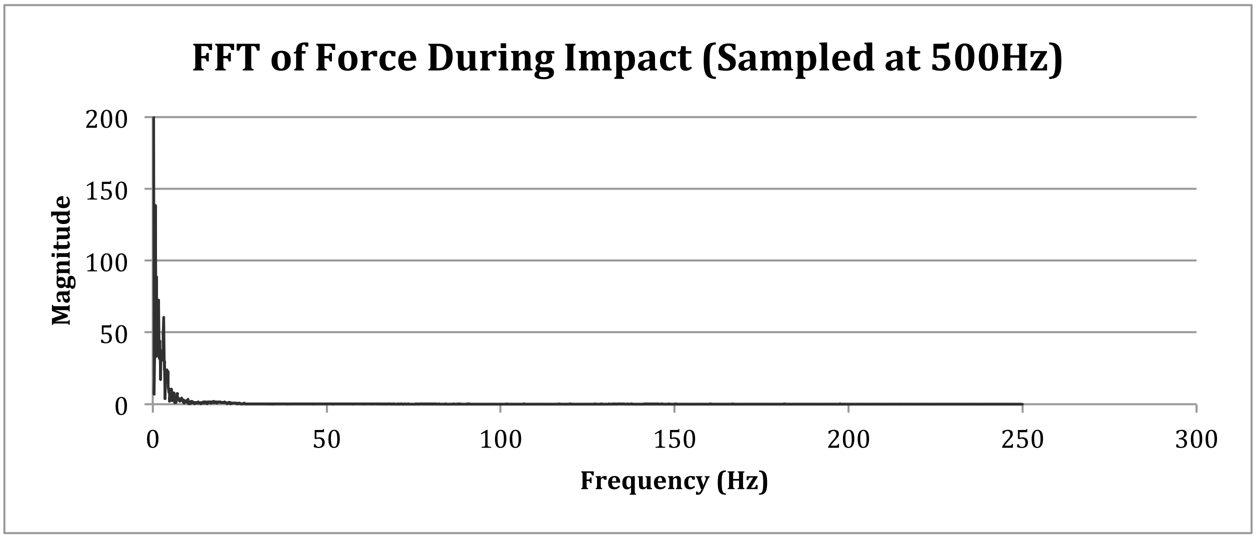

Figure C2. FFT of Force during impact sampled at 500Hz. Y-axis adjusted to be 0-200.

By visual inspection it is clear that the vast majority of data is below 10Hz and certainly less than 250Hz. We can therefore be confident that the sampling rate of 250Hz is sufficient to capture the force data.

Appendix D

MVCs & ROM

Figure D1. Erector Spinae MVC. Participant lifted their torso to horizontal and then maximally extended while being restricted by the researcher.

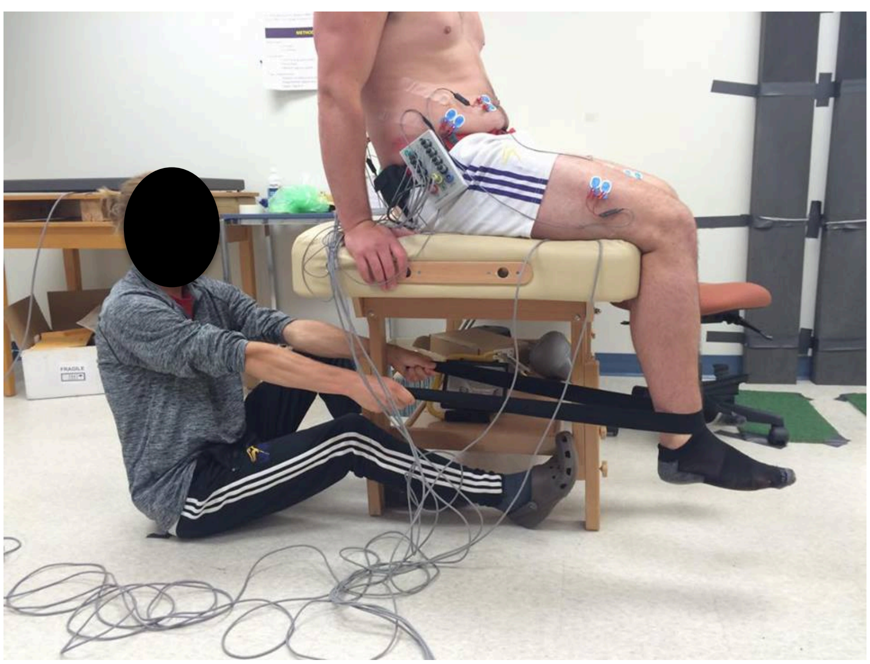

Figure D2. Quadriceps MVC. Participant would keep their knee at approximately 90 degrees and then ramp up to maximum extension while the researcher restricted this motion with a strap.

Figure D3. Abdominal MVC. Participant would perform a resisted sit-up, axial twists and lateral bends.

Appendix E

Apparatus & Set Up

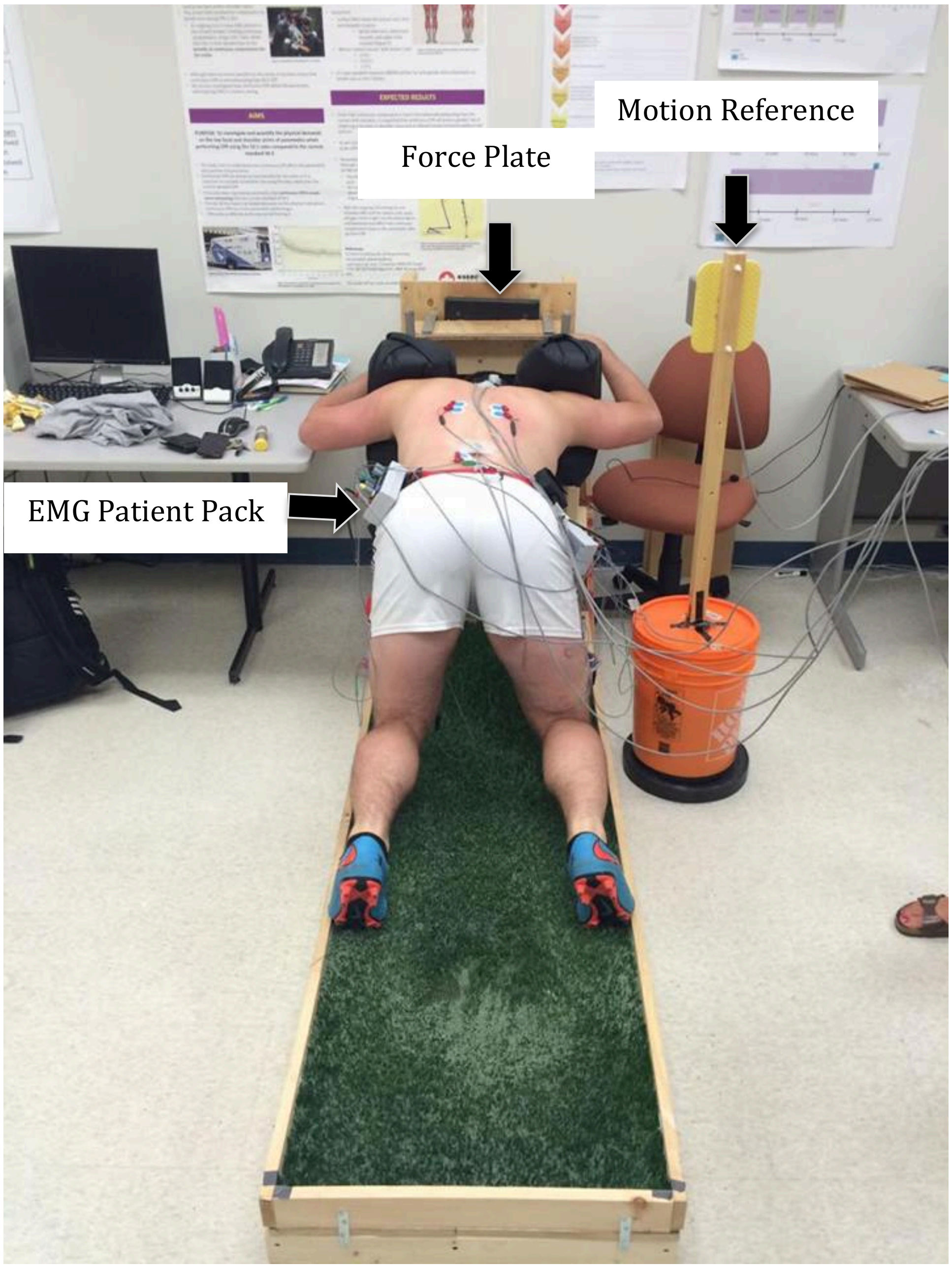

Figure E1. Scrum Apparatus.

Figure E2. Wall Sit Apparatus

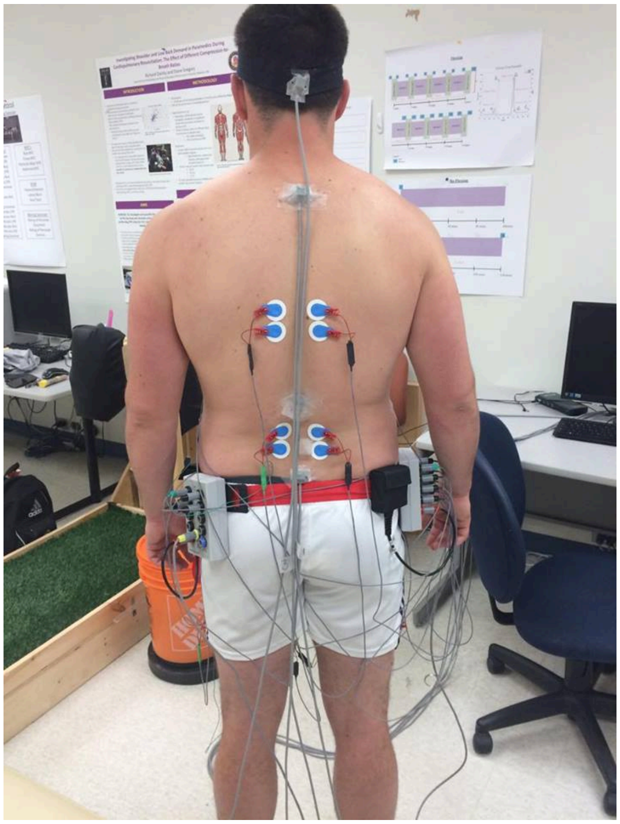

Figure E3. Back Motion and EMG Set-up.

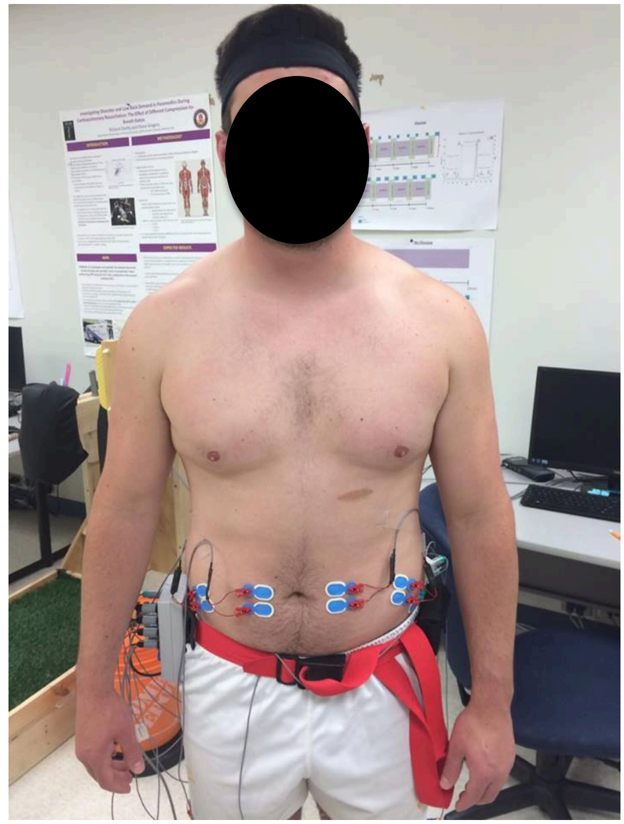

Figure E4. Abdominal EMG Set-up.

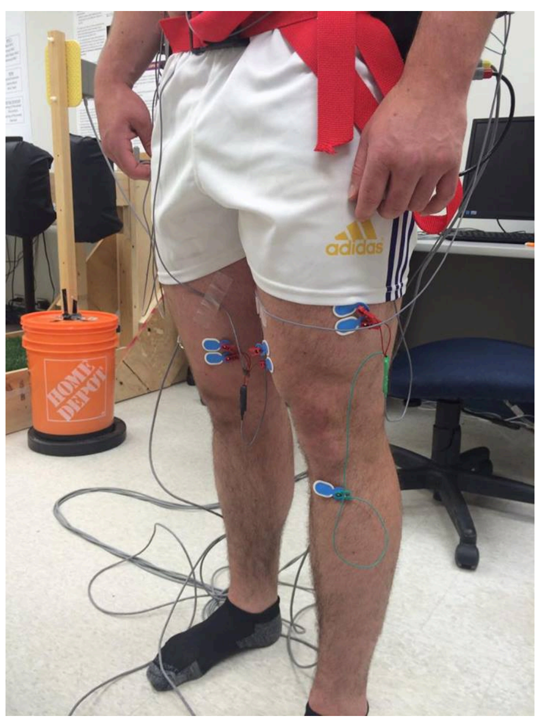

Figure E5. Quadriceps EMG Set-up.

Appendix F

Participant Information Form

Eligibility/Participant Form Participant Code (*Researcher*): ________________
First Name: ________________________ Last Name: ___________________________
Contact Phone #:____________________ Contact Email: ________________________
Age: _____________ Height: _______'________" Weight: _________________lbs
Circle Current Primary Position: Prop Hooker Lock Flanker 8-man
Other (specify): _____________________________
Number of years of experience playing rugby: ___________
How many years did you participate for the full season? _______________
Number of years that you have played a forward position (1-8): ______________

For each of the following levels of competition please indicate the **number of years** that you competed at each level (if applicable) and your primary position:

Junior Club (U14 or less): _____________ Position: ______________________
U14 (or less) Provincial: _____________ Position: ______________________
U14 (or less) National: _____________ Position: ______________________
High School: ________________________ Position: ______________________
U16 Club: ___________________________ Position: ______________________
U16 Provincial: _____________________ Position: ______________________
U16 National: _______________________ Position: ______________________
U18 Club: ___________________________ Position: ______________________
U18 Provincial: _____________________ Position: ______________________
U18 National: _______________________ Position: ______________________
U20 Provincial: _____________________ Position: ______________________
U20 National: _______________________ Position: ______________________
Men's Varsity: ______________________ Position: ______________________
Men's Club: _________________________ Position: ______________________
Men's Provincial: ___________________ Position: ______________________
Master's Club: ______________________ Position: ______________________

Have you had any significant injuries in the past year? (Circle) Yes No

If so please explain: ____

____

Do you have any current injuries? (Circle) Yes No

If so please explain: ____

____

Appendix G

Phases of the Scrum

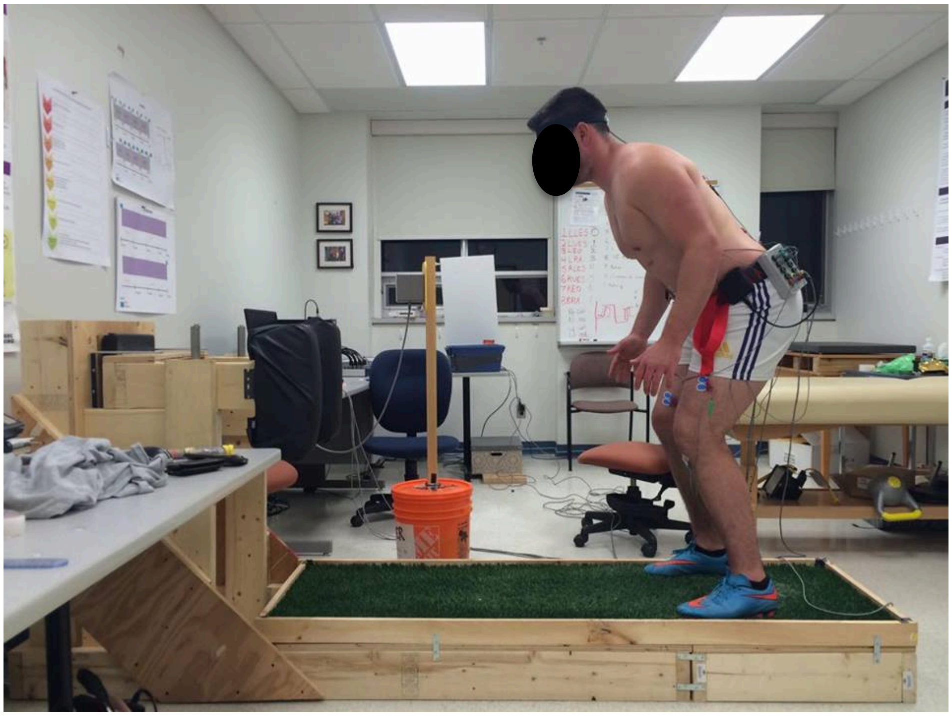

Figure G1. Preparation for the pre-contact phase.

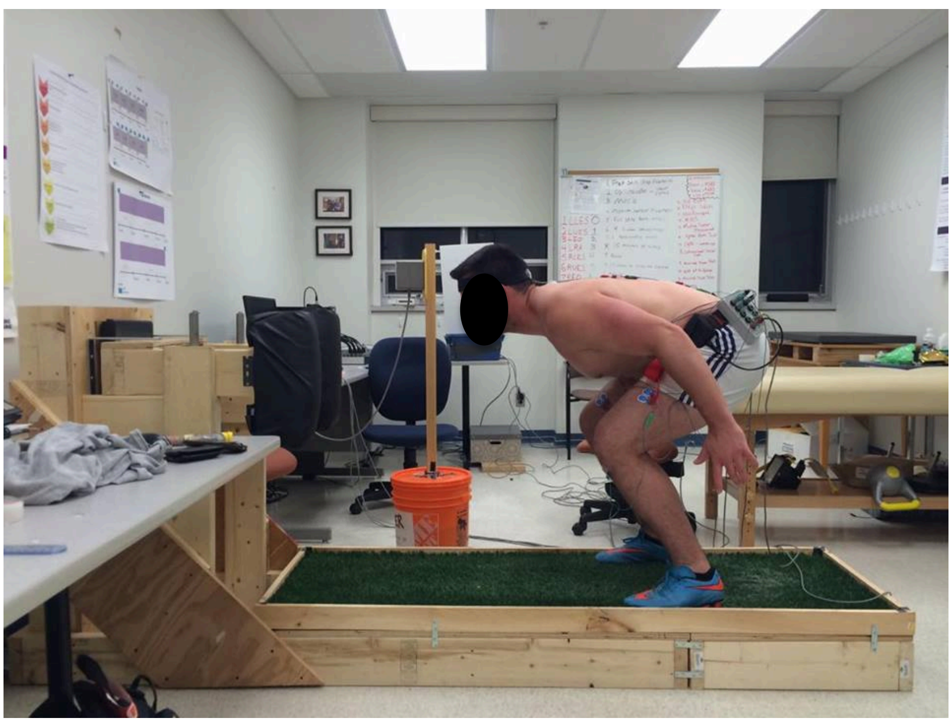

Figure G2. Crouch/Pre-Contact phase

Figure G3. Bind phase/Pre-Contact Phase

Figure G4. Set Phase/Contact phase (Impact Peak and Sustained Force)