Lumbar spine kinematics and kinetics during heavy barbell squat and deadlift variations.

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Abstract

Purpose: The primary purpose of this research was to compare barbell deadlifts and squats, as well as two technique variations within each lift, for their effects on lumbar spine kinematics and kinetics. The techniques compared within the deadlift condition were the low-hip deadlift (LHDL) and the high-hip deadlift (HHDL). The techniques compared within the squat condition were the high-bar squat (HBS) and low-bar squat (LBS). The outcome variables measured were peak lumbar flexion, L4-L5 and L5-S1 moments, and L5-S1 joint reaction force.

Methods: Data were collected and reported on 17 healthy competitive strength athletes (male = 12, female = 5, age = 26.5 ± 4.7 years, height = 176.1 ± 4.6 cm, body mass = 97.7 ± 22.3 kg). Participants completed three single lifts at 85% of their estimated one-repetition maximum using each lifting technique during a single session. Data were collected using an 8-camera 3D motion capture system and two in-ground force plates then processed using custom Matlab routines. Lumbar flexion was calculated using a custom kinematic driven lumbar spine model. Joint moments were calculated using inverse dynamics. Joint reaction force calculations were based on an equilibrium approach using a single-equivalent muscle model. A 2×2 factorial ANOVA with the factors of lift type (deadlift vs squat) and bar position (anterior vs posterior) was used to determine the effect of each main lift on the outcome variables. Significance for the ANOVA was set at $p<.01$. Planned paired samples *t*-test's were used to compare the effects of lift technique (LHDL vs HHDL and HBS vs LBS) on the outcome variables. Significance was set at $p<01$.

Results: Peak lumbar flexion, expressed as a percentage of maximal voluntary flexion, was significantly greater during the deadlift condition (76.76 ± 16.07%) in comparison to the squat condition (64.2 ± 19.8%, $p = .005$). Within the squat condition, peak lumbar flexion was

significantly greater for the LBS technique (67.9 ± 19.7%) when compared to the HBS technique (60.43% ± 19.79, $p<.001$). Normalized L5-S1 joint reaction force results displayed that within the deadlift condition, there was significantly greater average shear force during the LHDL technique (2.02 ± 0.23N) in comparison to the HHDL technique (1.98 ± 0.22N, $p=.004$). Within the squat condition, there was significantly greater peak shear force during the HBS technique (2.59 ± 0.42N) in comparison to the LBS technique (2.47 ± 0.40N, $p<.001$). Significant differences were not observed between or within lifting conditions for any of the other variables.

Conclusion: This is the first study to directly compare lumbar flexion and L5-S1 joint reaction forces between the barbell deadlift and squat, as well as the HHDL/LHDL and HBS/LBS technique variations within each lift. Results suggest that if normalized to barbell load, barbell squats create equivalent loading at the L5-S1 joint when compared to the deadlift. They also suggest significant differences in peak lumbar flexion and peak shear joint reaction force when comparing the HBS and LBS. Past research on barbell squat kinematics have perpetuated the assumption that the torso remains relatively rigid during this exercise; however, these findings indicated the lumbar spine undergoes considerable flexion when squatting to a depth slightly below parallel. Furthermore, the amount of lumbar flexion taking place seems to be influenced by the squat technique used and this can lead to significant differences in peak L5-S1 shear joint reaction force, a variable believed to be related to low back injury.

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Glossary of Terms

Kinetics: Examination of the forces acting on a system or object. This includes measuring the magnitude and direction of forces and moments (torques).

Kinematics: The characteristics of motion from a spatial and temporal perspective without reference to the forces causing that motion (Hamill et al., 2015). This includes the measurement of position, velocity and acceleration.

Moment (torque): The product of the magnitude of force and the perpendicular distance from the line of action of the force to the axis of rotation (Hamill et al., 2015). In other words, the rotational force created at a joint by forces not acting directly through the joint centre.

Load force: The amount of force applied to a joint by an external load, without taking into account the force created by muscular contraction. In the case of this thesis, this is the force applied to the joint by the weighted barbell and body mass.

Muscle force: The force applied to a specific joint as a result of muscular contraction.

Joint reaction force: The total amount force experienced at a specific joint determined by the summation of load force and muscular force.

Shear force: Unaligned forces acting in opposite directions on the inferior and superior rigid bodies comprising the joint.

Compression force: Aligned forces acting in opposite directions such that the superior and inferior rigid bodies of a joint are pressed together.

Barbell back squat: A common resistance training exercise performed by placing a weighted bar across ones back and flexing then extending at the torso, hip, knee and ankle resulting in a distinct decrease then increase in vertical bar position. For the purpose of this thesis, the barbell back squat refers to a squat completed as defined by powerlifting standards in which the crease if the hip passes just below the top of the patella.

High-bar barbell squat (HBS): A barbell squat technique where the bar is placed over top of approximately the first thoracic vertebrae. This squat technique it typically employed by novice lifters and weightlifters.

Low-bar barbell squat (LBS): A barbell squat technique where the bar is placed approximately over top of the fourth thoracic vertebrae. This technique is typically used by athletes competing in the sport of powerlifting and is sometimes referred to as the powerlifting squat.

Conventional barbell deadlift: A common resistance training exercise where a weighted bar is placed on the ground and aligned over top of the feet. The lifter is required to squat down, grasp the bar with their hands, and lift the bar while moving to a standing position before lowering the bar back to the ground.

Low-hip barbell deadlift (LHDL): A conventional barbell deadlift technique where the bar is placed over top of the first metatarsal phalangeal joint and directly beneath the shoulders. This creates a body position that resembles a squat, with a lower hip position and more torso inclination in comparison to the HHDL. This deadlift technique is typically used by weightlifting athletes and is sometimes referred to as a traditional deadlift technique.

High-hip barbell deadlift (HHDL): A conventional barbell deadlift technique where the bar is placed over top of the navicular bone and behind the shoulders, creating a shorter horizontal distance between the bar and ankle joint in comparison to the LHDL. This bar position results in a posture depicted by a higher hip position and less torso inclination in comparison to the LHDL. This technique is typically used by powerlifters.

Sumo barbell deadlift: A deadlift technique where the lifter places the feet in a very wide and slightly externally rotated position and grasps the bar between the legs, rather than outside of the legs as they do during the LHDL and HHDL. This is another deadlift technique occasionally utilized by powerlifters.

Neutral lumbar spine: This is the natural curvature of the lumber spine during unloaded standing. A neutral lumbar spine displays lordosis (concave curvature).

Lumbar flexion: Sagittal plane movement (primarily through rotation) in the lumbar vertebrae such that the posterior aspect of the entire lumbar spine transitions away from the neutral position towards a more linear or convex position. This can also be described as a reduction in lumbar lordosis.

Maximal lumbar flexion ROM: For the purpose of this thesis, this refers to the maximal amount of in-vivo lumbar flexion an individual was able to achieve during a voluntary trunk flexion task.

Lumbar extension: Sagittal plane movement (primarily through rotation) in the lumbar vertebrae such that the posterior aspect of the entire lumbar spine transitions from neutral to a position of increased concave curvature. This can also be described as an increase in lumbar lordosis.

Lumbar lordosis: The term used to describe lumbar spine curvature when in a concave position.

Lumbar kyphosis: The term used to describe lumbar spine curvature when in a convex position. The lumbar spine only displays a subtle convex curvature when it is at maximal flexion.

Powerlifting athlete (Powerlifters): One who engages competitively in the sport of powerlifting. The sport of powerlifting requires athletes to complete a single barbell back squat, barbell deadlift, and barbell bench press repetition with the highest load possible during a one-day competition. The winner is the athlete with the highest three lift total, which is determined by summating the amount lifted for each of the three exercises.

Weightlifting athlete (Weightlifter): One who engages competitively in the sport of weightlifting. The sport of weightlifting, sometimes called Olympic weightlifting, requires an athlete to complete the snatch and clean & jerk lifts with the highest load possible during a one-day competition. The winner is determined by who obtains the highest summation of load between the two lifts. The snatch and clean & jerk lifts combine deadlift, squat and overhead press movements into a single exercise. For the snatch, the bar is lifted explosively from the ground and propelled directly upwards, then caught overhead by dropping into a squat position, and finished by standing up out of the squat with the bar still overhead. For the clean & jerk, the clean phase consists of explosively lifting the bar from the ground and propelling it upwards, then catching it on the shoulders of the lifter in a squat position, at which point they return to standing with the bar resting on the shoulder. The jerk phase consists of propelling the bar overhead from the shoulders by doing a small jumping movement and straightening the arms.

CrossFit athlete: One who engages competitively in the sport of CrossFit. The sport of CrossFit requires athletes to complete workouts that combine exercises from weightlifting and powerlifting, as well as other training techniques, in order to create physically demanding circuit workouts. CrossFit competitions typically require athletes to complete a pre-determined circuit workout as fast as possible.

Competitive strength athletes: The term used to collectively describe individuals who compete in the sport of either powerlifting, weightlifting or CrossFit.

Low back injury: A term used to describe damage to any one of the lumbar spine tissues / structures to the point where it inhibits normal function. This includes abnormal damage to either the intervertebral disc, vertebral body, lumber ligaments or local lumbar spine musculature.

Mechanism of injury (MOI): A variable, under certain circumstances, known to contribute to the injury process.

Heavy load: A barbell load representing approximately 85% of the load an individual would be capable of lifting for a single repetition during a specific exercise.

Chapter 1: Scientific Outline

1.1 Introduction

The prevalence of low back pain and injury has caused significant scientific inquiry into lumbar spine structure, function, and loading (Adams et al., 1994; Bergmark, 1989; McGill et al., 1988; McGill et al., 2000; Panjabi, 2003). From this body of evidence, conclusions have been drawn as to what kinetic variables likely contribute to the injury process of various tissues surrounding the lumbar spine. It has also been made apparent that alterations in lumbar spine curvature (kinematics) effect the ability of the surrounding musculature to withstand external loading, thus identifying another contributing factor in the injury process (McGill et al., 2000; Tveit et al., 1994). Establishing basic mechanisms of injury (MOI) for various low back tissues has led to ongoing investigation of how different movement tasks influence spinal kinematics and kinetics, in hopes of limiting MOI conditions, thus reducing injury incidence (Eltoukhy et al., 2015; Hwang et al., 2009; McGill et al., 2012). In the field of ergonomics, this spawned the debate over whether the squat or stoop lifting technique is best to reduce low back injury, a debate that has yet to be conclusively settled (Bazrgari et al., 2007; Dreischarf et al., 2016; van Dieen et al., 1999). While extensive research into occupational lifting tasks has taken place and is often applied to exercise training situations, heavy resistance training exercises have not been thoroughly investigated.

Competitive strength athletes lift, push and pull loads under conditions that are unique from those experienced during occupational lifting tasks. While lifting activities in the workplace consist of low intensity high volume load exposure, strength athletes typically experience high intensity low volume load exposure. These athletes presumably experience the most shear and compressive stress within the spine out of any population given the amount of weight they are capable of lifting and the competitive nature of their respective sports. Estimates of peak joint reaction shear and compressive force at the L4-L5 joint for competitive male powerlifters in the 125kg weight class during the barbell deadlift have been reported as high as 1,762 N and 17,192 N, respectively (Cholewicki et al., 1991). In a practical sense, this equates to 180kg and 1,754kg of shear and compression, or roughly 1.4 and 14.0 times the lifters bodyweight. This population is at risk of sustaining injury during training and competition as these loads are near or above recommended limits (Gallagher et al., 2012; Hutton et al., 1982). This notion is supported by injury prevalence studies that found the low back to be the most common site of injury in competitive weightlifters and the second most common injury site in competitive powerlifters (Raske & Norlan, 2002; Calhoon & Fry, 1999). Furthermore, these exercises are now commonly being used across a variety of settings and populations for their positive effects on restoring motor function after injury and improving bone mineral density (Ebben et al., 2009; Watson et al., 2015). As a result, descriptive and comparative research on how barbell squat and deadlift exercises affect low back MOI variables is critical given their growing application across a breadth of populations and settings (clinical, rehabilitation, sport-specific training, general fitness training, etc.). Although the low back is a common injury location in weightlifting and powerlifting, overall injury occurrence is similar to that of other common sports (Calhoon & Fry, 1999). This indicates that while heavy squats and deadlifts do pose some inherent injury risk, these activities should not be viewed as being more dangerous in comparison to other athletic endeavors.

1.2 Literature Review

1.2.1 Lumbar Spine Biomechanics Literature

Specific attention has been paid to lumbar spine function and dysfunction across several research disciplines, primarily clinical biomechanics, mechanical engineering and ergonomics (Adams et al., 1994; Bergmark, 1989; McGill, 1997; McGill et al., 2000; Oxland, 2016; Panjabi 2003). Based on this research, it appears that two fundamental low back MOI's are the magnitude and direction of joint reaction force and the position of the vertebrae relative to one another (Adams et al., 1994; McGill, 1997; McGill et al., 2000). The magnitude and direction (i.e. compression vs shear) of joint reaction forces determines the amount and direction of mechanical stress placed upon the functional spinal unit (FSU); while the position of each vertebra relative to one another (cumulatively forming the lumbar spine curvature) influences how this stress is distributed across the various tissues of the FSU and the capacity of the spinal musculature to withstand external loading and provide spinal column rigidity during movement (Adams et al., 1994; McGill et al., 2000; Tveit et al., 1994). Thus, objectively describing how lifting activities effect kinetics and kinematics at the lumbar spine are the critical starting point to understanding how to perform lifts safely.

Low back injury has many forms. A brief summary of past research describing the interaction between lumbar forces and posture, as it relates to specific types of low back tissue overload, is required. The three common types of injury are disc herniation, muscle strain, and fracture (at the vertebral body, facets or neural arch). Disc herniation or fracture as a result of a single loading event during lifting activities are rare (McGill, 1997). Rather, cyclical exposure to high joint reaction forces and excessive lumbar movement can cause these tissues to breakdown and if sufficient recovery is not provided, forces which one was previously able to handle may surpass tissue tolerance limits resulting in failure (injury). This becomes an important consideration when attempting to decipher if specific lifting exercises are more likely to cause injury to these areas, as the cyclical exposure to the load (loading volume over time) must be considered. Muscle strain however appears to be more acute in nature as injury can be caused during a single lifting event that causes high force generation within the low back musculature (Calhoon & Fry, 1999). The primary takeaway is that when the lumbar spine is not at extreme ranges of motion, the exact kinetic and kinematic conditions that may damage the low back are specific to the type in injury in question. In other words, a lifting posture which is best to prevent risk of disc herniation may not be ideal for avoiding acute low back muscle strain.

In order to reduce risk of all low back injury forms when lifting heavy loads, full lumbar spine flexion and extension should always be avoided. Full flexion at the intervertebral joint level has been shown to cause tension within the posterior ligaments of the spine, which drastically increases compressive force within the joints (Adams et al., 1994; Cholewicki et al., 1992; McGill et al., 1988). Furthermore, when lumbar intervertebral joint rotation reaches 75% of full flexion, it creates high pressure distribution in the anterior region of the intervertebral disc, which may lead to increased risk of disk herniation (Adams et al., 1994). Lastly, full flexion of the entire lumbar spine reduces the moment arm length of the back extensor muscles at all lumbar joint levels, increasing the amount of force output required to generate extension moments at the lumbar joints. As the muscles become fatigued over repetitive use, this reduction in moment arm length increases risk of muscular strain as fatigue causes a reduction in peak force output (Binder-Macleod et al., 1998, Mair et al., 1996; Tveit et al., 1994). Extension at the lumbar intervertebral joints should also be avoided when lifting as this causes the vertebral apophyseal joints to become load-bearing, which can cause damage to the neural arch under very low loads (Adams et al., 1994). The culmination of these findings resulted in Adams et al. recommending lumbar intervertebral joint posture between 0-75% of full flexion when withstanding high compressive loads (Adams et al., 1994). Interestingly, well trained strength athletes are taught to avoid significant lumbar movement while lifting, yet low back injuries still occur. This implies that joint forces may still vary enough within this range of motion (ROM) to cause tissue damage at the lumbar spine. As a result, we need a better understanding of how lifting variations may affect the lumbar loading while the global lumbar spine curvature remains in a neutral zone.

While the causes of low back injury present as relatively simple from a mechanical loading perspective, variability amongst individuals' anatomical structure and lifestyle makes the injury process far more complex. Anatomical variability in the passive spinal structure influences the magnitude of force required to reach tissue failure and produce injury. Furthermore, postural variations as a result of different types of daily activity can cause residual changes to the spinal structure, similarly influencing injury characteristics. So although mechanical mechanisms of injury for the low back are similar across individual's, the exact magnitude of force and conditions causing any form of injury may be individual specific.

1*.2.2 Barbell Squat and Deadlift Literature*

The barbell squat and deadlift are foundational exercises in the majority of athletic strength and conditioning and rehabilitation programs. Competitive strength sports such as powerlifting, weightlifting and CrossFit complete these lifts (or similar variations) during competition. Some evidence has been presented describing the kinematic and kinetic effect these lifts have on the lumbar spine.

A small body of evidence has described lumbar kinematics during the squat and deadlift exercises. These studies have investigated how horizontal displacement of the knee joint, stance width and sex effect lumbar spine curvature during the barbell squat exercise. It would appear that performing a squat where the knees travel horizontally past the toes during descent (unrestricted squats) decreases forward torso lean as well as a reduces lumbar flexion at the bottom of the squat position (Campos et al., 2016; Fry et al., 2003; List et al., 2013; Walsh et al., 2007). Research by McKean et al. also displayed that the lumbar spine undergoes more flexion when squatting with a narrow stance (feet positioned in-line with ASIS anatomical landmarks) in comparison to a wide stance and that females tend to undergo less lumber flexion during the squat than males (McKean et al., 2010). In addition, they also observed that the lumbar spine moves away from neutral and into a more flexed curvature once the barbell (load) is being supported on the back and shoulders prior to squat descent. Walsh et al. reported changes in lumbar kinematics as a result of different loads and using a weight belt (Walsh et al., 2007). Findings of this study were difficult to interpret due to lack of objective definitions surrounding the variables analyzed and defining lumbar neutral as the angle of the lumbar spine while the load was placed on the back, when this in fact represents an anatomically flexed lumbar posture (McKean et al., 2010). This resulted in a misinterpretation in stating the lumbar spine goes into hyperextension when beginning lift ascent at the bottom of the squat exercise.

Cholewicki et al. utilized video fluoroscopy to analyze the movement of the lumbar vertebrae during very heavy deadlifts (Cholewicki et al., 1992). Their findings displayed that the lumber spine does not reach maximal levels of flexion during the deadlift, indicating the ligaments are not likely to be a primary contributor to extension moments created during this lift.

In summary, it seems conclusive that during the barbell squat, lumbar spine flexion increases during lift descent. There also appears to be a relationship between torso angle and lumbar flexion such that a more horizontal torso position (decreased torso inclination) during a squat result in greater lumbar flexion (Campos et al., 2017). During a near maximal load deadlift, the lumbar spine does not appear to reach maximal in-vivo flexion ROM in spite of the entire segment visually appearing completely flexed (Cholewicki et al., 1992). The exact amount of peak lumbar flexion taking place during the barbell squat and deadlift at submaximal loads relative to in-vivo tissue limits at the lumbar spine is unclear.

To the knowledge of the author, five studies have been published reporting lumbar joint force estimates during the barbell deadlift or squat. With the exception of Eltoukey et al., all of these studies calculated joint reaction forces using an equilibrium based approach. Muscular force contributions were estimated using multiple approaches, with the WATBAK model utilized by Cholewicki et al. accounting for the greatest amount of individual muscles.

Cappozzo et al., reported compressive joint reaction force estimates between 6-10 times bodyweight at the L3-L4 joint when participants completed barbell half squat with loads between 0.8 to 1.6 times bodyweight (Cappozzo et al., 1985). Lander et al. conducted a study analyzing the biomechanics of the barbell squat exercise when comparing a normal bar to an experimental "inverted U" bar, which lowered the vertical position of the load resulting in a lowered system centre of mass (COM) (Lander et al., 1986). They concluded that intra-abdominal pressure decreased as the system COM was positioned closer to the ground; however, this did not significantly affect estimated shear and compression joint reaction force at L5-S1. Although not directly reported, it is estimated that compression and shear joint reaction forces were approximately 8.7-9.1 and 4.0-4.2 times bodyweight respectively. Shortly after, Granhed et al.

reported the estimated compressive forces taking place in the L3-L4 joint during very heavy deadlifts (Granhed et al., 1987). A strong relationship was found between compressive force measured in the lumbar spine and corresponding bone mass density. They also noted the importance of reducing moment arm distance between the low back joints and barbell as this had a significant effect on estimated joint loading when using the muscle model presented by Shultz et al. (1981). Cholewicki et al. conducted a study on estimated lumbar spine kinetics during the barbell deadlift exercise at a Canadian National Powerlifting Competition (Cholewicki et al., 1991). Joint moments as well as joint reaction forces were compared between conventional and sumo deadlift techniques. The sumo posture significantly decreased moments and load shear force at the L4-L5 joint. This was said to have resulted from a shortening in horizontal distance between the bar (external load) and lumbar spine during the sumo lifting technique. Interestingly, joint shear force was not significantly different, indicating the musculature at the low back was capable of offsetting the high load shear force experienced during the conventional deadlift. Mean values reported by Cholewicki indicate that on average, disc compression and joint shear force at L4-L5 in male powerlifters is approximately 14.9 and 2.1 times bodyweight respectively. The final study on lumbar kinetics was conducted by Eltoukhy et al. for the purpose of validating a computer based model to estimate lumbar vertebrae position, allowing more accurate estimates of load forces taking place during heavy weightlifting exercises (Eltoukhy et al., 2015). Load shear and compression results at the L4-L5 joint during the deadlift were only half the magnitude of those reported by Cholewicki et al.; however, this was attributed to the participants in the Cholewicki study lifting twofold greater loads. This study however did not estimate joint reaction forces. It should be noted that when attempting to determine loading characteristics of the lumbar spine as it relates to potential injury, calculating the force contribution at the joint of both the loaded barbell and musculature should be desired as simply determining how much force the external load places upon a specific joint is not sufficient.

In summary, joint reaction compression and shear forces in the low back during a submaximal barbell squat appear to be approximately 6-10 and 4.0-4.2 times bodyweight respectively. During a maximal barbell deadlift, these values are in the range of approximately 14.9 and 2.1 times bodyweight respectively. The absolute magnitude of force appears to increase at when moving from the L1 to L5 level, with shear force specifically showing a large increase at the L5-S1 level (Eltoukhy et al., 2015). During the barbell squat, the highest force values take place at the bottom of the lift as high force impulse is required when transitioning from descent to ascent (Cappozzo et al., 1985; Lander et al., 1986). During the deadlift exercise, reducing the horizontal distance between the barbell and the body reduces moments at the low back; however, exactly how this affects joint reaction forces is unclear (Cholewicki et al., 1991; Granhed et al., 1987).

No studies have directly compared lumbar kinetic and kinematic variables between the deadlift and squat; however, a body of evidence exists describing other distinct differences between these exercises. Comparative research has shown that they differ in EMG activity of the legs and low back musculature as well as ankle, knee, hip joint and torso angles (Escamilla et al., 2001; Escamilla et al., 2000; Ebben et al., 2009; Hales et al., 2009 Hamlyn et al., 2007; Nuzzo et al., 2008). This, in combination with the fundamental difference in vertical bar position for each exercise indicates they place unique demands upon the body, which may lead to distinct differences in lumbar spine kinetics and kinematics.

Competitive strength athletes and recreational lifters often utilize different squat and deadlift technique variations for the purpose of achieving a desired training outcome or simply to lift more weight. Majority of the current literature on barbell back squat variations has focused on directly comparing squat depth or restricted vs unrestricted anterior knee displacement (Bryanton et al., 2012; Campos et al., 2016; Chiu et al., 2017, Fry et al., 2003; List et al., 2013). Two other technique variations within the back squat are the high-bar squat (HBS) and low-bar squat (LBS). Lifters performing a LBS place the load at approximately the fourth thoracic vertebrae rather than overtop of the first thoracic vertebrae, which is the common bar placement for the HBS. The HBS technique is utilized primarily by weightlifters and recreational lifters whereas the LBS technique is more commonly used by powerlifters. Wretenberg et al. and Swinton et al. conducted the only research studies directly comparing kinetic and kinematic effects between these technique variations (Swinton et al., 2012; Wretenberg et al., 1996). Results from this research indicate significant differences in torso inclination, hip angle, knee angle and shin angle. Findings also indicate that the LBS may create higher moments at the hip joint, but lower moments at L5-S1 in comparison to the HBS (Swinton et al., 2012; Wretenberg et al., 1996). Glassbrook et al. recently published a review article comparing several differences between the HBS and LBS, the kinematic and kinetic findings of which support findings presented by Swinton and Wretenberg (Glassbrook et al., 2017) This indicates that when investigating how the squat exercise influences lumbar spine loading and curvature, effects of each specific technique should be considered.

The barbell deadlift exercise can be completed using several different techniques. As mentioned, past research has compared conventional and sumo deadlift technique for various kinematic and kinetic variables (Cholewicki et al., 1991; Escamilla et al., 2000). Another deadlift technique that has been recently compared to the conventional deadlift is the hexagonal (HEX) bar deadlift (Swinton et al., 2011). The hexagonal barbell allows the lifter to grasp the bar and position the hands directly beside the legs rather than in front. Results from this study displayed no differences in torso angle but a significant reduction in ankle, hip and low back moments during the HEX deadlift (Swinton et al., 2011). Methods surrounding exactly how low back moments and torso angle was calculated were not clearly defined. Lastly, the emergence of two distinct conventional deadlift techniques has created some confusion as to which warrants a proper conventional deadlift. Weightlifters often employ a low-hip deadlift (LHDL) technique while powerlifters typically use a high-hip deadlift (HHDL) technique. Similar to the kinematic differences between the HBS and LBS, the HHDL technique creates a significant reduction in torso inclination, knee flexion and shin angle (Unpublished pilot study data collected in our lab). The only research study comparing these technique variations concluded that the HHDL caused less total horizontal bar displacement during the duration of the lift, suggesting it is a more mechanically efficient technique (Hancock et al., 2012). As noted by Granhed et al., subtle changes in horizontal bar position can significantly affect forces experienced at the low back, indicating comparison between the LHDL and HHDL may be important when investigating lumbar kinetics (Granhed et al., 1987).

The association between lumbar kinematics and hip joint range of motion is a secondary topic of interest directly related to the barbell squat and deadlift. It is perpetuated in strength and conditioning that decreased maximal hip flexion ROM is a primary factor influencing lumbar flexion during the deadlift and squat exercises. As these exercises require large amounts of hip flexion, one who lacks the required ROM at the hip joint may obtain that ROM through the nearest most motion segment, the lumbo-pelvic region in this case. While commonly not considered, the anatomical cause of hip ROM restrictions may influence how this factor contributes to lumbar flexion.

Research examining the anatomical causes of reduced hip flexion ROM have established two distinct categories, those being soft tissue impingement and soft tissue restraint (Safran et al., 2013; Turley et al., 2013). Soft tissue impingement occurs when regions of either the femoral head or femoral neck come into contact with the joint capsule. Soft tissue restraint describes a restriction in hip ROM due to tension within the musculature or ligaments crossing the hip joint. Soft tissue restraint at the hip joint has not been studied in great detail; however, it appears the ligaments of the hip only seem to restrict hip extension motion, and not hip flexion due to their anterior anatomical position in relation to the hip joint (Moore et al., 1992; Safran et al., 2013). This means any lack of hip flexion due to soft tissue restraint is likely to be caused by tension within skeletal muscle rather than the ligaments. Only one study has investigated whether skeletal muscles may limit hip flexion and concluded that removing skeletal muscles from cadaveric specimens did slightly increase hip flexion limits (Safran et al., 2013). Since all muscles were removed between conditions, this study does not give insight into which specific muscles limit hip flexion.

Soft tissue impingement has been more thoroughly analyzed due to its clinical implications surrounding the development of osteoarthritis at the hip joint (Tannast et al. ,2008; Zadpoor et al., 2015). Abnormalities in the anatomy of the femoral head and/or joint capsule as well as improper positioning between the femoral head and acetabular fossa can cause premature contact between these two structures during hip flexion, therefore reducing ROM (Loubert et al., 2013; Safran et al., 2013; Tannast et al. ,2008; Turley et al., 2013; Zadpoor et al., 2015). While multiple factors influence hip flexion ROM, investigating its general association with lumbar flexion could establish whether this topic warrants more detailed investigation.

1.2.3 Current Gaps in the Literature

Several gaps exist in the literature surrounding how heavy barbell squats and deadlifts effect lumbar kinematic and kinetic variables related to low back injury. Firstly, there is no literature directly comparing the squat and deadlift at submaximal loads, as well as the previously described technique variations, for how each exercise influences peak lumbar flexion during the lift. Secondly, past research investigating kinematics at the lumbar segment during these lifts has done so using a variety of angle measurements (Campos et al., 2016; Fry et al., 2003; List et al., 2013; McKean et al., 2010; Walsh et al., 2007). While helpful in describing the general movement pattern at the lumbar region, these results make interpreting potential injury implications difficult. For one to adequately understand how these lifts influence joint reaction force magnitude and its likely distribution across the FSU, expressing lumbar flexion as a percentage of maximal flexion ROM proves beneficial as it permits comparisons with ergonomics literature; something that has yet to be done during the squat or the deadlift at submaximal loads (Adams et al., 1994). Thirdly, no previous research investigating the effects of these exercises on joint reaction forces have estimated the muscular force contribution using an approach that accounts for changing musculature moment arm lengths and line of action in response to different degrees of lumbar flexion. This is critical as previous research has noted significant changes in lumbar curvature do take place during these exercises and such changes affect estimates of joint reaction shear and compression force (Campos et al., 2016; McKean et al., 2010, van Dieen et al., 1999). Lastly, no research has directly compared joint reaction forces at the lumbar spine between the squat and deadlift or between the specific technique variations utilized by powerlifters and weightlifters.

Filling these voids in the literature will provide additional insight into the effects these common resistance training exercises have on lumbar kinematics and kinetics. This will allow others to further analyze how these conditions affect load distribution across the FSU and the associated individual tissue loading; results of which will provide conclusions surrounding the injury process as a result of these specific lifts and techniques.

1.3 Purpose Statement and Hypothesis

1.3.1 Purpose Statement

The primary purpose of this research was to investigate how deadlifts, squats and two technique variations within each condition (LBS vs HBS and LHDL vs HHDL) influence estimated lumbar kinematics and kinetics. Specifically, these lifts and the two techniques within them were compared for their effects on estimated lumbar flexion angle, peak and average L4-L5/L5-S1 moments, and peak and average L5-S1 joint reaction force. The secondary purpose was to examine if maximal hip flexion ROM during unloaded movements was associated with lumbar flexion during each lifting condition such that low peak hip flexion angles resulted in high peak lumbar flexion angles during the deadlift and squat.

1.3.2 Hypotheses

The primary lumbar kinematics hypotheses were that between conditions, a greater peak lumbar flexion angle would be present in the deadlift condition when compared to the squat; while within conditions, HHDL and LBS techniques would result in greater peak lumbar flexion when compared to the LHDL and HBS, respectively. These hypotheses were formulated around the premise that lifts which require the torso to be in a more horizontal position, relative to the ground, will result in greater amounts of lumbar flexion.

The primary kinetic hypotheses were that between conditions, average and peak moments would be greater during the deadlift condition in comparison to the squat condition; while within conditions, average and peak moments would be greater during the LHDL and LBS when compared to the HHDL and HBS respectively. In regard to L5-S1 compression and shear force compared between conditions, it was hypothesized that the deadlift would result in greater average and peak compression and shear force when compared to the squat; while within lifts, average and peak compression would be greater during the LHDL and HBS and shear would be greater during the HHDL and LBS respectively. These hypotheses were formulated based on the knowledge that the lifts and techniques will alter the moment arm length between the barbell and lumbar joints resulting in a reduced moment and furthermore, a more vertical torso angle will result in greater amounts of compression force and decreased shear due to the orientation of the joints in relation to the barbell (Cholewicki et al., 1991; Escamilla et al., 2000; Escamilla et al., 2001).

The hypothesis surrounding the association between hip flexion ROM and peak lumbar flexion was that the two variables would display a significant negative correlation during both conditions such that lower maximum hip flexion ROM values would be associated with greater peak lumbar flexion values. This hypothesis is based on the premise that individuals with reduced hip flexion ROM will flex more at the lumbar spine in order to obtain the total movement ROM required to complete each lift.

Chapter 2: Methods

2.1 Study Design

This study utilized a cross-sectional within subject's experimental design. Each participant performed the two lift conditions (barbell deadlift and barbell squat) and two technique variations within each lift condition (HHDL, LHDL, HBS and LBS). The lift condition and technique order was randomized initially by condition then within each condition. Six repetitions of each condition (three with each technique variation) were performed and data were averaged across repetitions. Participants also completed three ROM assessment trials prior to lifting (standing trunk flexion, standing hip hinge and bodyweight deep squat). All data were collected during a single lab testing session lasting approximately 120 minutes. Dependent measures obtained from the ROM movement trials were three-dimensional locations of markers placed on the feet, tibias, femurs, pelvis, sacrum and spinous process of the 12th thoracic vertebrae (T12) and 6th cervical vertebrae (C6). The dependent measures collected during all lifting trials were ground reaction force (GRF) magnitude and location, along with the three-dimensional locations of markers placed on the feet, tibias, femurs, pelvis, sacrum, T12, C6, acromioclavicular joints, ulnar radial notches (elbows), ulnar styloid processes (wrists), the lateral sides and front of the head and the barbell. From these measures, all primary outcome measures were extracted (as described in section 2.4) and compared within subjects between lift types and techniques within each lift.

2.2 Participants

Healthy competitive strength athletes were recruited to voluntarily participate in this study. Recruitment consisted of promoting the research study at various local fitness facilities frequented by competitive strength athletes. The promotion method used was the distribution of recruitment flyers at each fitness facility (Appendix A). This study was approved by the University of Saskatchewan Biomedical Research Ethics Board Data for research in human subjects (Appendix B). All participants provided their written informed consent prior to data collection (Appendix C).

Inclusion criteria was having taken part in a CrossFit, weightlifting, or powerlifting competition within the past year. Participants were excluded if they had a significant injury within six months of data collection and no prior experience performing the LBS technique. A significant injury was defined as an injury that required the participant to alter or refrain from resistance training for greater than two weeks. The LBS was the only technique variation acknowledged in the exclusion criteria due to Wretenberg et al. reporting that the lift variation was distinct from the standard squat and therefore required significant practice in order to be done correctly (Wretenberg et al., 1996).

An a priori sample size estimate was not feasible due to lack of research analyzing the outcome measures in question. Instead, a desired sample size was collected based on previous research examining kinematic differences between similar squat and deadlift variations. These studies were able to show significant differences in various kinematic measure with sample sizes ranging from n=6 to n=39. (Escamilla et al., 2000; Escamilla et al., 2001; Hancock et al., 2012; McKean et al., 2010).

A total of 18 people were recruited and all participated in this study; however, data collected from one participant was unusable due to marker occlusion. As a result, data was analyzed for 17 participants (male: n=12, and female: n=5) between the ages of 22-38.

Participants' mean (±SD) age, height, body mass and training experience was 26.5 ± 4.7 years, 176.1 ± 4.6 cm, 97.7 ± 22.3 kg, and 5.7 ± 3.5 years respectively.

2.3 Testing Protocol

2.3.1 Participant Intake

Upon arriving at the laboratory, participants completed their informed consent and verbally answered a series of resistance training questions, the answers to which were recorded by the researchers. Participants were asked to report their most recent training one-repetition maximum (1RM) estimate for the barbell deadlift and squat exercises. Further to this question, they were asked if that one-repetition maximum was achieved while wearing a weightlifting belt. They were also asked to report their most recent competition date and the type of competition they competed in. Lastly, they were asked how long they had been engaging in regular resistance training (3X weekly minimum). After answering all preliminary questions participants changed into the required clothing for data collection. Male participants wore mid-thigh length compression shorts while females wore athletic shorts (mid-thigh length or less) and a sports bra.

2.3.2 Anatomical Landmarking

Data collection protocol began with participants undergoing anatomical landmarking. Several bony prominences representing specific anatomical structures were identified through palpation; and the corresponding locations marked by an X drawn on the surface of the skin with a non-toxic marker. All palpation and landmarking was completed by second-year Masters of Physical Therapy (MPT) students from the School of Physical Therapy, University of Saskatchewan. A total of four students conducted landmarking throughout all data collection, with a minimum of two students completing the landmarking procedure during each data collection session. Anatomical locations marked were the spinous processes of C6, T10, T12, L1, L3, L5, left and right PSIS, and both the medial and lateral epicondyles of the left femur and right femur. These specific bony prominences were selected for marking to help ensure the consistency of the kinematic data collected.

2.3.3 Warm-up Protocol

Participants were then required to complete a semi-standardized warm-up that consisted of light aerobic exercise, mobility exercises, and a series of sub-maximal squats and deadlifts. For the aerobic portion, participants completed five minutes of low-intensity aerobic exercise on a cycle ergometer. Following this, all participants were asked to complete any mobility exercises they would typically engage in prior to training or competition. Exercise selection was left to the participants' discretion; however, all exercises completed during this stage of the warm-up could be classified as dynamic stretches and/or myofascial release. This was done to replicate real-world conditions as much as possible. The typical warm-up employed consisted of 5-minutes of foam rolling followed by 5-minutes of dynamic stretching. Researchers began the lifting portion of the warm-up by describing and demonstrating the different lifting conditions to each participant, as previously described. Exercise technique corrections were then made during the subsequent lifts if necessary. The warm-up culminated with participants completing a single set of two repetitions for each technique (HBS, LBS, HHDL and LHDL) at a load of 65% 1RM. Load progression during the warm-up was left to the discretion of each participant; however, participants were required to reach 65% of their 1RM by their fourth warm-up set for each lifting condition and a maximum of four reps was allowed during each set. Warm-up lifting condition order was matched to the randomized order determined for the data collection trials.

2.3.4 Motion Capture Set-up and Calibration

A spherical reflective marker 9mm in diameter was placed on the skin at C6, T10, T12, L1, L3, L5 and bilaterally on the posterior suprailiac spine (PSIS), Figure 2.1. Spherical reflective markers 14 mm diameter were placed bilaterally at the anterior suprailiac spine (ASIS), acromioclavicular joint, radio-ulnar notch, styloid process of the wrist, femoral condyles, ankle malleoli, heel and first metatarsophalangeal joint. Semi-rigid 4-marker clusters were secured to the lateral aspect at approximately the mid-point of each femur, tibia, and the centre of the sacrum. Participants wore a headband equipped with three spherical reflective markers 14 mm in diameter and aligned to the centre of the forehead and directly above each ear. Individual markers were secured to the skin using hypoallergenic adhesive tape while the clusters were secured using the same adhesive tape and vet wrap (3M). After completing a static standing T-pose calibration trial, spherical markers were removed from the ASIS, femoral condyles and ankle malleoli.

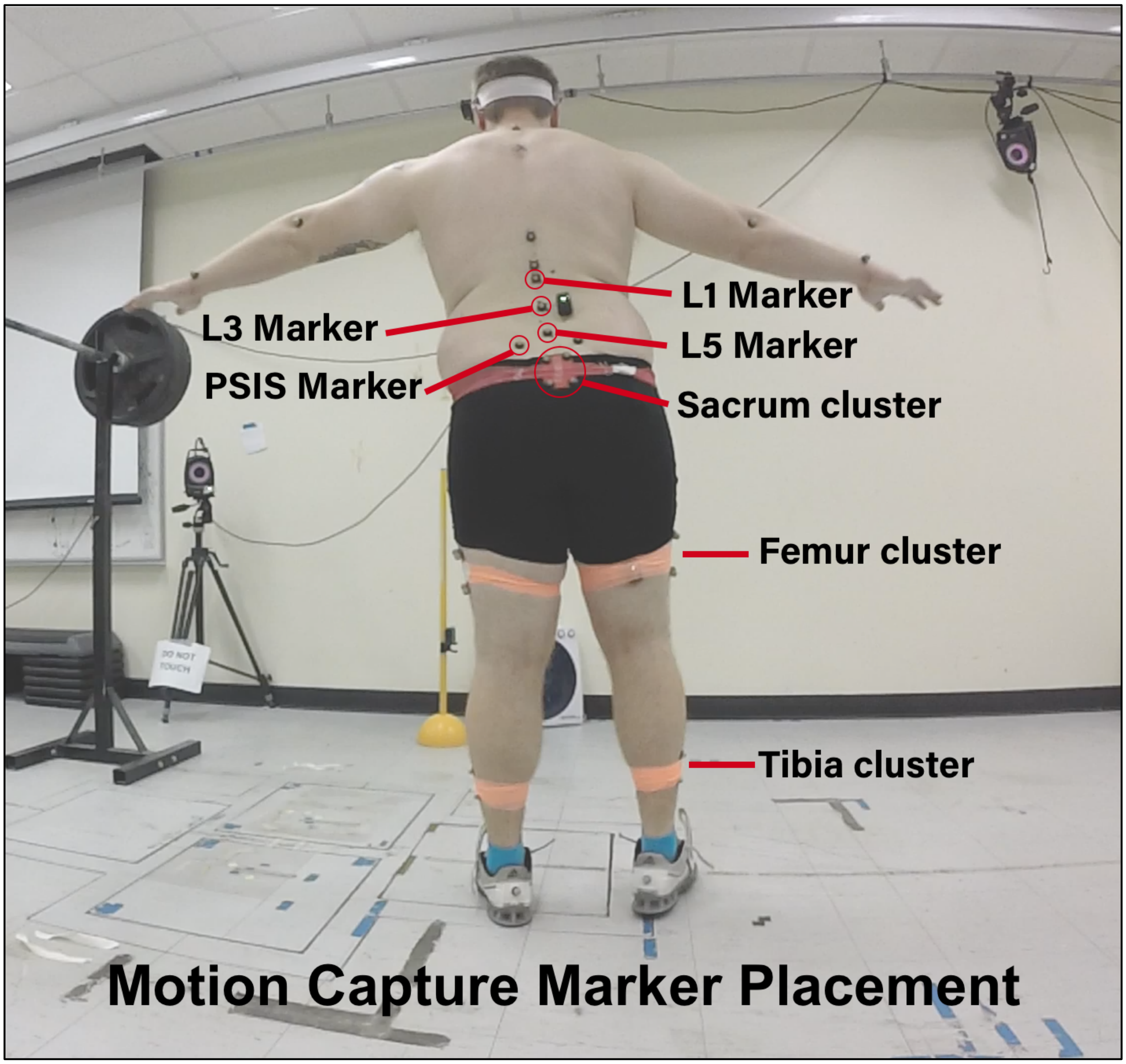

Figure 2.1: Participant 3D motion capture marker placement during the range of motion and lifting trials.

2.3.5 Range of Motion Movements

The ROM movements were completed to assess and quantify maximum flexion ROM at the lumbar spine and hip joints. Two different hip flexion ROM movements were utilized to account for large differences in knee flexion between the deadlift and squat conditions, which influences maximum hip flexion ROM. Thus, condition specific (deadlift and squat) hip flexion ROM tests were required. Three trials of a single repetition were completed for each ROM task.

Standing trunk flexion - Participants were instructed to tuck their chin to chest and then fold the torso forward and down as far as possible. Foot width was standardized at shoulder width. Muscle electromyography was recorded (results are not reported) for these tests to help ensure myoelectric silence was achieved in the lumbar region erector spinae, thus indicating near maximal voluntary lumbar flexion (Cholewicki et al., 1992).

Hip-hinge - Participants were instructed to stand with their feet placed shoulder width apart, slightly bend at the knees, and flex forward from the hips as if they were reaching down to set-up for a deadlift. They were then given the extra instruction to refrain from moving through the low back as much as possible when bending forward and that they should not stop the movement until feeling a slight stretch in the back of the legs (hamstrings).

Bodyweight deep squat – While standing, participants were instructed to assume their preferred squat stance (feet slightly wider than parallel with subtle external rotation at the hip) and slowly descend into the lowest possible squat position without losing balance. Arms were extended straight in-front of the body to provide counter balance at peak squat depth.

2.3.6 Lift Types and Techniques

Each lifting technique was completed for three sets of a single repetition at approximately 85% of each participants' self-reported 1RM for each lift type (squat and deadlift). If the participant had achieved their self-reported 1RM while wearing a weightlifting belt, the load was decreased by an additional 15% as this equipment has been shown to significantly increase intra-abdominal pressure allowing one to lift a greater loads (Harman et al., 1989; Lander et al., 1992). The exact amount a weightlifting belt is capable of increasing a lifters 1RM has not been reported in the literature; however, experienced lifters anecdotally report 1RM value increases between 10-15%. A two-minute rest period was taken between each individual lift and a five-minute rest was taken during the transition between lift types. All lifts were completed using a standard 45 lb male competition barbell, Figure 2.2.

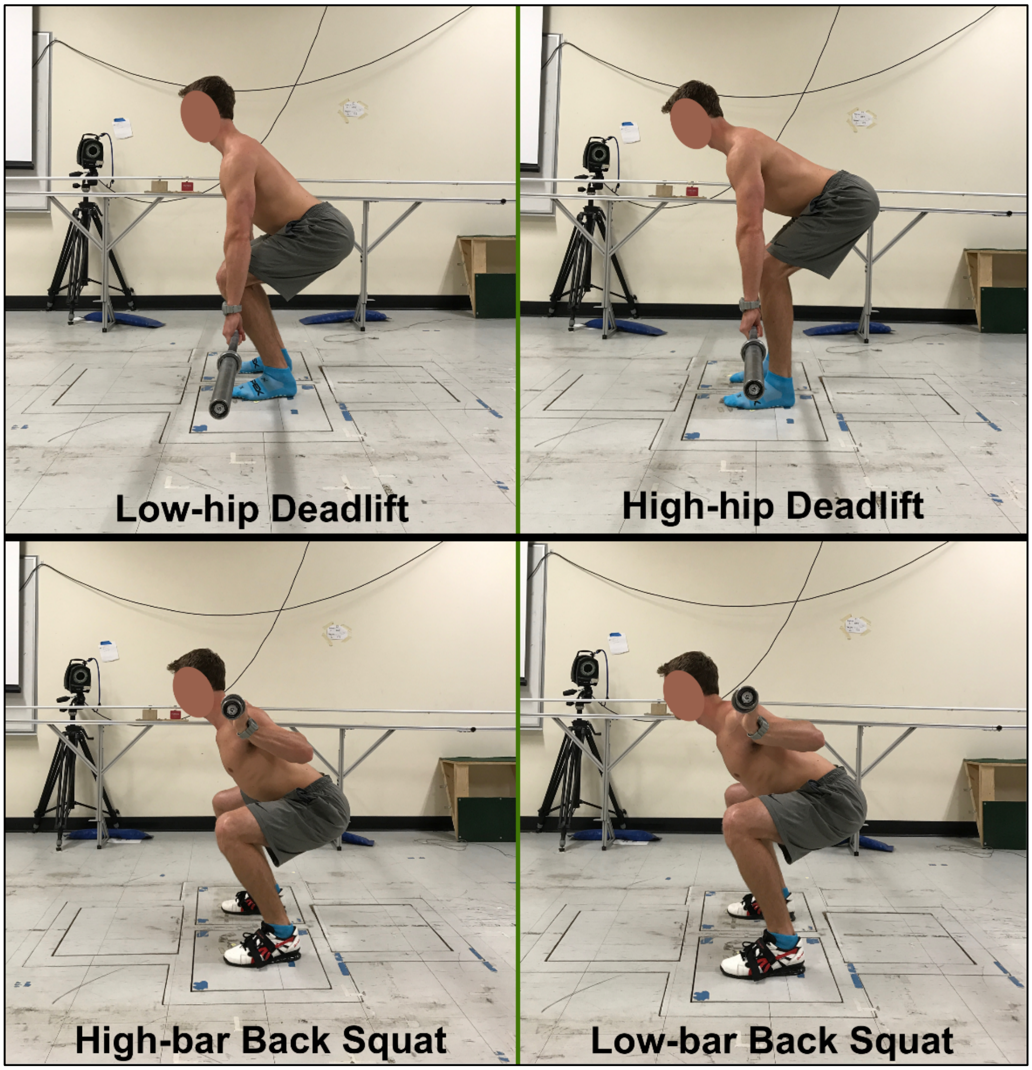

Figure 2.2: Images displaying the two lift types and specific techniques analyzed within each lift type.

<u>Squat condition</u> – All participants wore their standard weight training shoes while completing the squat conditions. Squat depth was standardized and controlled between all repetitions using a pair of laser activated timing gates (Brower Timing Systems, Draper, UT). Prior to completing the barbell squats, participants were asked to perform a bodyweight squat to a depth where the

crease of their hip was just below the top of the patella. While holding that position, the laser timing gates (placed on either side of the participant) were adjusted such that the beam created between each device was obstructed by the most inferior aspect of the gluteals, resulting in a high-pitched ringing sound. Participants were instructed to descend into a squat until they heard the ringing sound (indicating they had reached a depth slightly below parallel), at which point they began ascent. This depth was based upon the competition squat depth requirements as determined by International Powerlifting Federation (International Powerlifting Federation Technical Rules Book, 2016). Foot position was marked on the floor using tape to ensure consistency between all lifting trials.

<u>HBS technique</u> – Participants began by approaching the loaded barbell, which was supported just below shoulder height by a standard competition squat stand. They then placed the barbell across their back directly beneath the spherical marker that was placed over top of the 6th cervical vertebrae. They then lifted the bar from the squat stand and stepped backwards in order to align each foot with the tape markings. One repetition was completed, then participants placed the barbell back on the squat stands and began their rest period.

<u>LBS technique</u> – Participants began by approaching the loaded barbell, which was supported just below shoulder height by a standard competition squat stand. The bar was placed over top of the 4th thoracic vertebrae, which was identified by an X marked on the skin during the landmarking process. This represents a typical bar location for a LBS; however, some highly trained powerlifters are capable of positioning the bar even lower on the back during this technique (Wretenberg et al. *MSSE*, 1996). The remainder of the protocol was completed identical to the HBS.

Deadlift condition – All deadlifts were completed in socks which were purchased from a local trampoline park (APEX, Saskatoon, SK) and provided to the participants. The socks contained rubberized grips on the bottom to ensure adequate traction. Small X's were placed on the socks over top of the navicular bone and the first metatarsal phalangeal joint of each foot. Once the barbell was placed in the proper position, it was wedged on either side using rubber weights to help prevent any horizontal movement. Participants were allowed to use either a standard or alternating grip for the deadlift condition; however, they were required to use the same grip for all deadlift trials. Protocol for standardization of the LHDL and HHDL techniques was slightly adapted from the protocol reported in previous literature (Hanckock et al., 2012). Foot placement was marked on the ground using tape to ensure consistency between trials. Rubber plates and laser timing lights were used to help ensure the barbell moved directly vertical at initial liftoff from the ground. To prevent rolling, the barbell was wedged in place using 45 lb Olympic rubberized plates. The laser timing lights were aligned such that the beam connecting the lights was positioned vertically at the top and horizontally at the anterior most edge of the barbell plates. As a result, initial bar path was considered vertical (a valid repetition) only if the barbell plate broke the plane of the laser causing a high-pitched ringing sound.

LHDL technique – Participants begin by placing each foot over its marked location. After this, the barbell was positioned directly above the marking on the sock identifying the location of the first metatarsal phalangeal joint. Participants were then instructed to set-up for the deadlift by grasping the bar and adjusting their posture such that the bar made contact with the shins and was directly beneath the shoulders. From this position, they were instructed to complete a single deadlift such that the bar traveled in a completely vertical line at initial lift off.

HHDL technique – Once participants aligned their feet on the marks on the floor, the barbell was positioned directly above the navicular bone marking on the socks. Participants were then instructed to set-up for the deadlift by grasping the bar and adjusting their posture such that the bar made contact with the shins and was behind the shoulders. From this position, they were instructed to complete a single deadlift.

2.4 Data Acquisition

2.4.1 Preliminary Kinetic and Kinematic Data

Kinematic data were collected for all trials (including the ROM trials) using an 8 camera 3D motion capture system (F20 cameras, MX Ultranet, NEXUS version 2.1.1, VICON, Centennial, CO) at a sampling rate of 100Hz. The trajectory data were then inspected and cropped and trajectory gaps filled with the NEXUS software (version 2.3, VICON, Centennial, CO). Kinetic data were collected using two in-ground force plates (45.7 x 53.3 cm, Model OR6-7, AMTI, Watertown, MA), one beneath each foot, at a sampling rate of 2000 Hz. Force plate and kinematic data were synchronously collected using the NEXUS software and VICON hardware.

Raw kinematic and kinetic data were then processed using custom Matlab routines (v2006b, Mathworks, Natick, MA). The 3D marker trajectories were low-pass filtered at a cut-off frequency of 8Hz using a 4th order Butterworth filter. The initial standing pose was used to identify lower limb joint centers and segmental coordinate systems. The hip joint locations were estimated using a regression equation that utilizes the ASIS and PSIS locations (Harrington et al., 2007), while the knee and ankle joint centres were estimated as the midway point between the femoral condyles and the malleoli respectively. Coordinate systems were then established for the pelvis, femurs and tibia based on published standards (Wu et al., 2002). Transforms were established between these coordinate systems and their associated marker clusters and the 3D segmental kinematics and joint centre trajectories were calculated from the cluster kinematics using a least squares approach (Söderkvist et al., 1993). The shin angle was calculated as the angle between the long axis of the tibia segment and the global vertical axis using a dot product, Figure 2.3. Torso inclination angle was calculated as the angle between the torso segment (defined inferiorly by the hip joint centre and superiorly by the acromioclavicular joint) and the global horizontal axis using a dot product, Figure 2.3. Knee angles were calculated as the relative 3D orientation of the tibia coordinate system with respect to the femur and hip angles were calculated as the relative 3D orientation of the femur coordinate system with respect to the pelvis, Figure 2.3. Only the flexion/extension angles for the knee and hip were used. Pelvis tilt was expressed relative to the global coordinate system. Joint angles were expressed relative to the angles during the standing calibration pose, which were assumed to be neutral joint positions. All ground reaction forces were low-pass filtered at a cut-off frequency of 20Hz using a 4^{th} order Butterworth filter. Locations of the center of pressure for each plate were calculated and expressed in the motion capture global coordinate system. Force and centre of pressure data were then down sampled at a rate of 1 to 20 to match the kinematic data sampling rate.

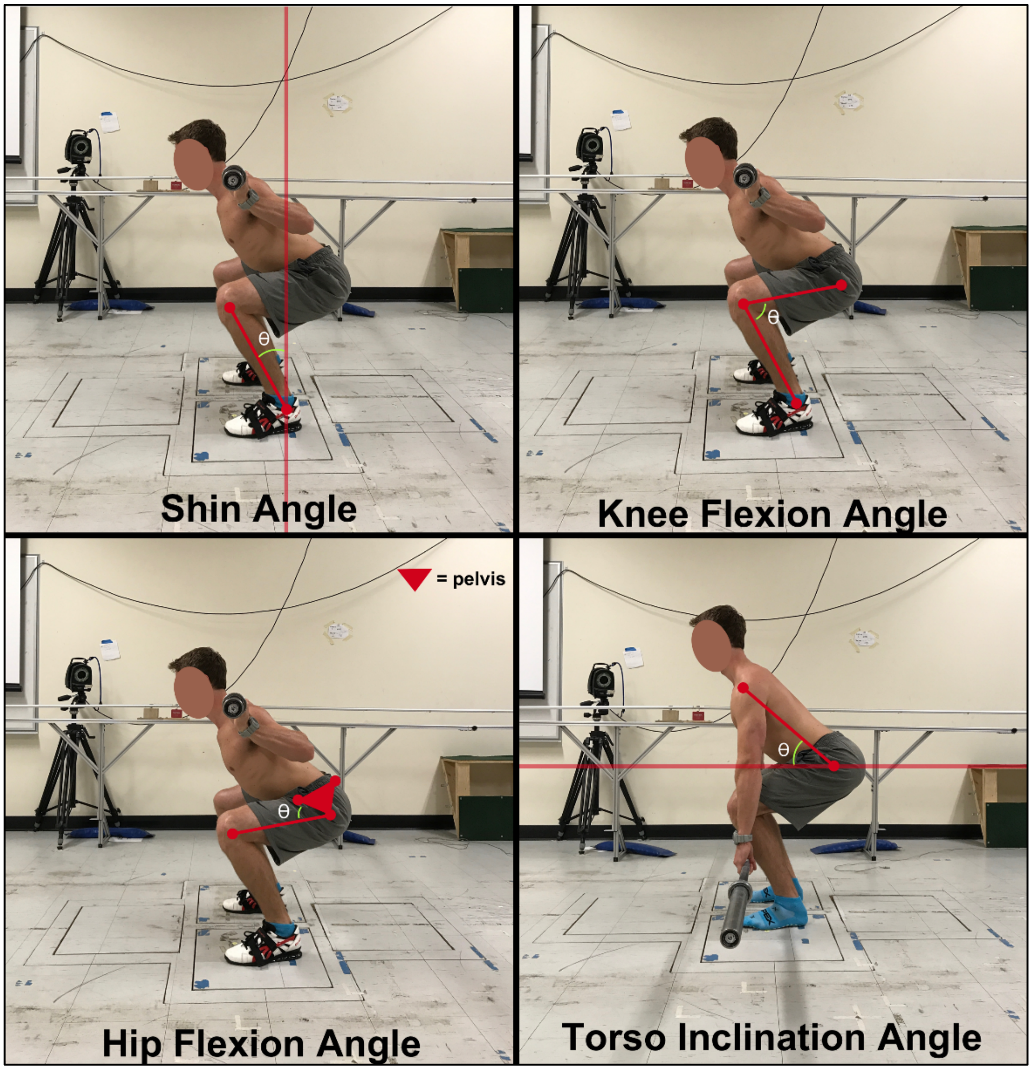

Figure 2.3: Diagrams displaying the relative body segments from which torso, hip, knee and shin kinematics were measured.

2.4.2 Bar Kinematics and Lift Cycle

During all lifting conditions, barbell movement was measured by tracking a rigid cluster containing 4 spherical markers attached to PVC pipe and placed on one end of the barbell. From the cluster, the centre point of the PVC pipe was calculated using a custom Matlab routine throughout the entire lift, the data from which was calculate bar displacement and determine the timing of each lift cycle.

The beginning point of each lift cycle was defined by the first instance of vertical plane movement of the barbell and the ending point defined by the prolonged cessation of barbell movement. To account for slight differences in barbell velocity between participants and lifting trials, the lift cycle was represented as a percentage of total lift time, Figure 2.4.

Figure 2.4: Images displaying the approximate body position during the squat and deadlift trials at 0%, 25%, 50%, 75% and 100% of the lift cycle.

2.4.3 Lumbar Spine Kinematics

Lumbar spine curvature was measured using a custom planar kinematic lumbar spine model, Figure 2.5. The model was implemented in Matlab using published measurement estimates for all five lumbar vertebral bodies and spinous process dimensions (Panjabi et al., 1992), while IVD height was assumed to be 10 mm. The model consisted of three degrees of freedom (DOF); a single lumbar flexion angle and the horizontal and vertical coordinate of the centre of the L5 vertebral body. Each of the vertebral bodies was rotated a given percentage of the lumbar flexion angle based on the relative amount of sagittal plane rotation that takes place at each individual lumbar joint during flexion (Christophy et al., 2011; Neubert et al., 2014). The lumbar flexion angle DOF was similar to the approach used when measuring lumbar angle from a radiographic image (Wong et al., 2006). Estimations of the locations of the L1, L3 and L5 markers could be obtained from the model based on the locations of the spinous processes. For each frame of movement data, the experimental and model-derived locations of the three lumbar markers, expressed in the pelvic coordinate system, were compared. The values of the model DOF were automatically adjusted for each frame of data until the minimum root mean square (RMS) error between the experimental and model-derived positions of the markers was achieved. This minimization was performed using a simplex optimization implemented in the Matlab fminsearch routine (Lagarias et al., 1998). Once the minimum RMS error between the experimental and model-derived position was achieved, the position of each lumbar vertebrae was adjusted to represent the approximate position of the entire lumbar spine, Figure 2.6. The mean RMS error measurement between the experimental and model-derived marker locations among all participants was 4.3mm per marker. This value equated to a mean error in lumbar flexion angle of 3.5 degrees.

In order account for individual differences in anatomy, the model was first scaled to each individual participant using data from the trunk flexion ROM task. A single linear scaling factor was used to scale all of the vertebral body dimensions while a single rotation, applied to L5, was used to account for the static lumbosacral angle. These two parameters were estimated by running a nested optimization on the trunk flexion ROM trial such that the outer loop optimized the scaling factors while the inner loop optimized the three main kinematic model DOF (again finding the minimum RMS error between measured and predicted lumbar markers). The scaled model was then used to estimate the lumbar flexion angle for all subsequent movements for that participant.

Lumbar flexion angle data from all trials were normalized to the maximal lumbar flexion angle obtained during the trunk flexion ROM task and expressed as a percentage. As such, lumbar flexion values of 0% represent the participant's lumbar spine curvature during quiet standing and a value of 100% represents the lumbar spine curvature during the trunk flexion task when the torso was in the fully flexed position. As a result, all flexion values represent the cumulative rotation of each lumbar vertebrae away from their position during relaxed upright standing. Angle measurements are not representative of the exact lumbar lordosis or kyphosis angle, rather they describe the sagittal rotation of the lumbar vertebrae away from the lordosis angle present during relaxed standing in the flexion direction.

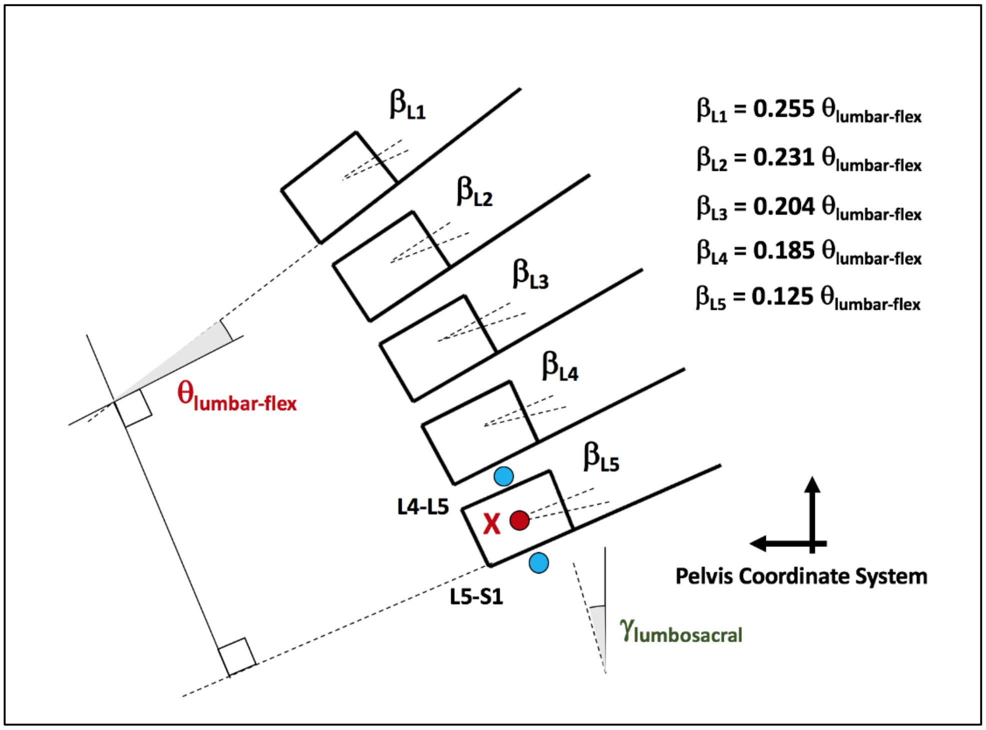

Figure 2.5: Planer kinematic lumbar spine model used to measure lumbar spine flexion angle. Lumbar flexion was measured by taking the angle of the intersecting lines running perpendicular to the inferior vertebral body of L5 and parallel at the inferior vertebral body of L1. The beta coefficient represents the relative amount of rotation permitted at each vertebral level during lumbar flexion.

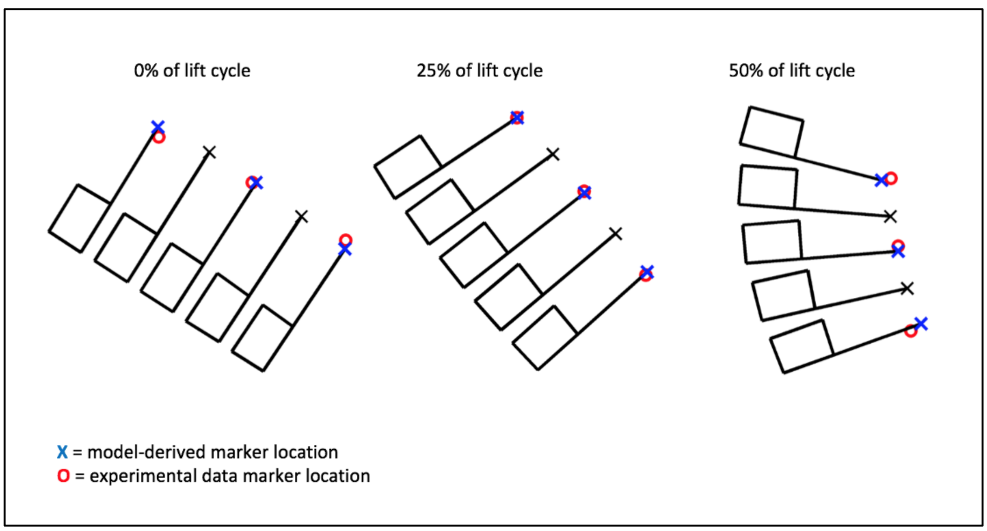

Figure 2.6: Positioning of the lumbar spine model after minimizing root mean square error between the experimental and model-derived data. The model is displayed at three different time frames during the deadlift cycle to display the change in lumbar model positioning driven by the experimental marker data.

2.4.4 Lumbar Spine Kinetics

Joint moment estimates:

Custom Matlab routines were used to calculate L4-L5 and L5-S1 joint moments using a quasi-static inverse dynamics formulation. Working upwards from the ground, force data, centre of pressure locations and ankle, knee and hip joint centres were used to calculate joint moments and net reaction forces at each joint in both limbs. All moment calculations were completed in 3D and followed an iterative approach beginning at the feet such that the moment taking place at each joint took into account the reaction force contributions of the moment generated at the distal connecting segment. The left and right hip moments were both applied to the pelvis segment in order to calculate the moment acting upon the L5-S1 joint. Only sagittal plane moment values were used as inputs to the SEM model used to determine force contributions of the musculature. Due to the relatively slow movement and large external forces present during the lifts, the linear and angular segmental accelerations were neglected in the joint moment calculations (Escamilla et al., 2000; Lander et al., 1990). Lower limb and pelvic segment masses and centres of mass were estimated using published data (de Leva et al., 1996). L5-S1 and L4-L5 joint locations were obtained from the lumbar spine model by taking the halfway point between each vertebrae. Moment values were normalized to total load (body weight + barbell load) and participant standing height.

Muscle force estimates:

An equilibrium approach was used to estimate the force generated by the musculature at the L5-S1 joint. This approach assumes that the musculature crossing the lumbar joints generated a moment that opposes the moment calculated using inverse dynamics, thus creating equilibrium. The musculature moment arm length and line of action (direction of pull relative to the joint) at the L5-S1 joint was determined using a single equivalent muscle (SEM) model regression equation developed by van Dieen et al. (van Dieen et al., 1999), Figure 2.7. SEM models are derived through estimating the relative force contributions of all muscles crossing a specific joint by measuring their individual cross-sectional area (force contribution), distance from the joint centre (moment arm length) and line of action (muscle angle orientation). Once such values are determined, all muscles are combined to create a single, hypothetical muscle with a numerical moment arm length and line of action that approximates the action of all muscles contained within the model (McGill et al., 1987; McGill et al., 1988). The van Dieen SEM model presents the only equation which accounts for changes in muscle moment arm length and line of action during a range of lumbar flexion. The van Dieen model range results in a moment arm length of 4.0cm with a 100° line of pull at the highest degree of flexion and a moment arm length of 5.2cm with a 134° line of pull in the neutral position. The lumbar spine angle data obtained from our custom lumbar spine model (previously described) was used to derive position specific SEM moment arm length and line of action values. The formula reported by van Dieen to determine moment arm length was as follows: $l = a\theta^2 + b\theta + c$, where l is equal to the moment arm length and θ is equal to the relative rotation between the rigid thorax segment and pelvis (represented in degrees). The formula to determine line of action was as follows: $x = d\theta + e$, where x is equal to the line of action (in degrees). The exact coefficient values for $a, b, c, d,$ and e, along with their ranges across varying anatomical assumptions are reported by van Dieen (van Dieen et al., 1999). The SEM force was then calculated using the following equation: $F = M \div l$, where F was equal to SEM force (in newtons), M was equal to the joint moment calculated during inverse dynamics (in newton meters) and l was equal to the moment arm length (in meters) obtained from the van Dieen equation. Compressive and shear components of the SEM force where then calculated using the following formulas: $MCF = cos^{-1}(x - 90) \times F$ and $MSF = sin^{-1}(x - 90) \times F$, where MCF was equal to the muscle compressive force (in newtons), MSF was equal to the muscle shear force (newtons), F was equal to the calculated SEM force (in newtons), and x was equal to the line of action (in degrees) calculated with the van Dieen formula. The line of action obtained from the van Dieen model was subtracted by 90 degrees to represent a line of action running perpendicular to the L5-S1 joint rather than parallel.

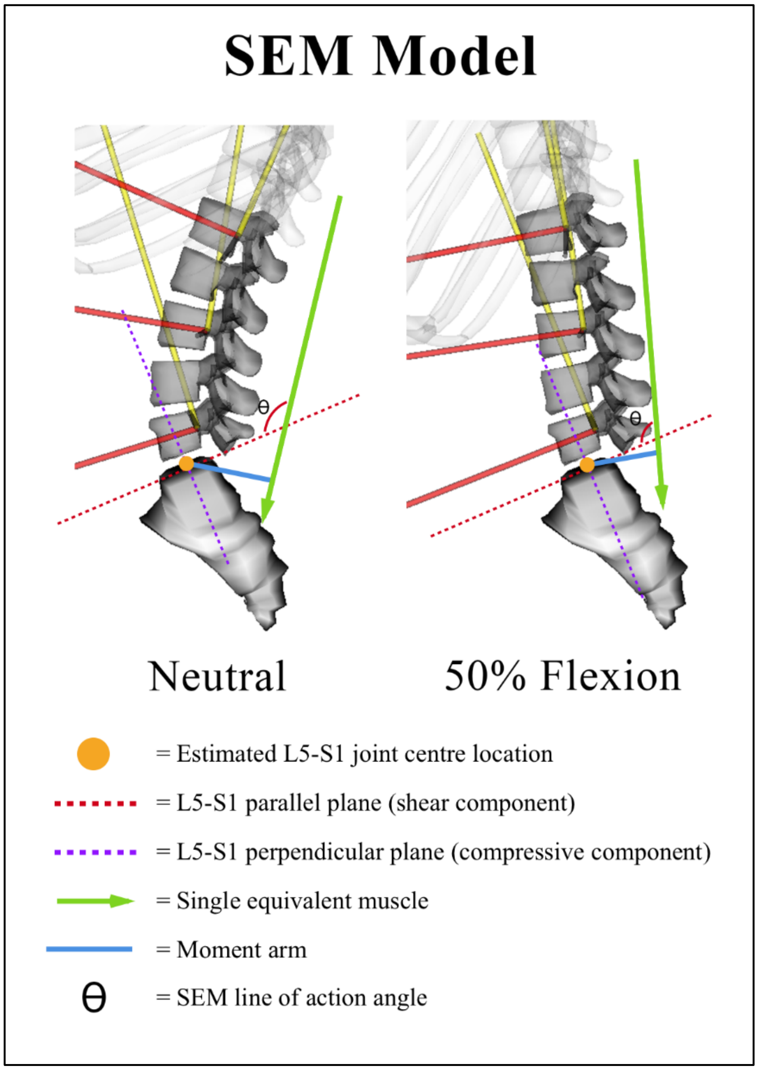

Figure 2.7: Single equivalent muscle model (SEM) used to estimate force contributions from the back extensor musculature at the L5-S1 joint (van Dieen et al., 1999).

Joint reaction force:

The reaction forces created at the L5-S1 joint were calculated by taking the summation of the compressive and shear force components created by the external load (body mass + the loaded barbell) and estimated force generated by the back extensor musculature (MCF and MSF). All joint reaction force values were then normalized and expressed relative to total load (body mass + barbell load).

2.4.5 Hip Flexion Range of Motion

Peak hip flexion ROM for each participant for the deadlift condition was determined by taking the mean maximum hip flexion angle value obtained during the three hip-hinge ROM trials. Peak hip flexion ROM for the squat condition was determined by taking the mean maximum hip flexion angle value obtained during the three bodyweight deep squat ROM trials. Values were represented as an average between the right and left leg.

2.5 Statistical Analysis

For statistical analysis, values for each dependent variable were created by taking the mean value of all three lift technique trials for each participant. Due to marker occlusion, there were five participants for which measures could not be obtained from all three lifting trials for some lifting conditions; resulting in a value representing the mean across two trials or simply a single trial value.

All data followed a normal distribution as determined by standard error of skewness and kurtosis values falling within the $\pm$ 2 range.

2.5.1 Comparison Between the Deadlift and Squat Lifting Conditions

The effects of the deadlift and squat conditions on all lumbar spine kinematic and kinetic variables were examined using a 2×2 factorial ANOVA. The factors used were lift type (squat vs deadlift) and bar position (anterior vs posterior). Only results from the lift type factor were analyzed and reported. The accepted significance value was set at $p<.01$ for all dependent variables compared using the factorial ANOVA. A conservative p value was used to protect against possible type I error as a result of running several ANOVA's with data collected from the same sample set. All values are expressed as mean ± standard deviation. Statistical analysis for all tests was completed using SPSS, version 24 (Chicago, IL).

2.5.2 Comparison of Techniques within the Deadlift and Squat Lifting Conditions

A planned comparison between technique variation within both the squat and deadlift conditions on each dependent variable was conducted using paired samples *t*-tests. Significance was accepted at $p<.01$ for comparisons made between all dependent variables. All values are expressed as mean ± standard deviation. A conservative p value was used to help protect against possible type I error due to comparing several dependent variables within the same sample. The planned comparison approach to analyze technique within each lift type (squat vs deadlift) was utilized as the effect of bar position was not of primary interest; Therefore, a 2×2 factorial ANOVA was simply used as a means of determining the presence of a main effect for lift type and not to investigate if an interaction effect was present between lift type and bar position in order to justify post-hoc *t*-tests.

2.5.3 The Effect of Hip Mobility on Lumbar Flexion

The relationship between maximal hip flexion ROM and peak lumbar flexion taking place within each lifting condition was examined using a correlation analysis. Hip flexion values from the hip-hinge movement were correlated with peak lumbar flexion angle values during the deadlift condition. Hip flexion values from the bodyweight deep squat movement were correlated with peak lumbar flexion values during the squat condition. Significance was accepted at $p<.05$.

Chapter 3: Results

3.1 Participant Lifting Characteristics

Details regarding the lifting loads of all of the participants are presented in Table 3.1. The mean (±SD) load lifted during data collection for male participants during the barbell squat and deadlift conditions was 149.5 ± 33.5kg and 172.3 ± 34.1kg respectively. For female participants, the mean (±SD) load lifted during the barbell squat and deadlift conditions was 84.6 ± 17.1kg and 103.4 ± 19.2kg respectively.

Lumbar posture results generated from the planer kinematic lumbar spine model are reported in Table 3.2. The mean (±SD) lordosis angle during quiet standing, peak kyphosis angle during maximum flexion and total flexion ROM were -35.4 ± 9.9º, 38.8 ± 13.3º, and 74.2 ± 9.8º respectively. Refer to figure 6.2 in the appendices for a visual representation of the planar kinematic model positioning during quiet standing and peak flexion.

For the deadlift condition and techniques, lumbar flexion, L4-L5 and L5-S1 moments and joint reaction forces peaked between 4.1-10.2% of the lifting cycle, Table 3.2. For the squat condition and techniques, lumbar flexion, L4-L5 and L5-S1 moments and joint reaction forces peaked during 47.8-56.8% of the lifting cycle, Table 3.2.

Participant ID	Sex	Competition type	Training Experience (years)	Squat load (kg)	Deadlift load (kg)	Relative squat load	Relative deadlift load
1	Male	PL	5	217	239	1.62	1.79
2	Male	PL	4	180	213	1.29	1.53
3	Female	PL	2	91	91	1.23	1.23
4	Male	PL	10	143	184	1.51	1.94
5	Male	PL	4	111	141	1.23	1.56
6	Male	PL	5	143	177	1.57	1.95
7	Male	PL	4	195	211	1.62	1.75
9	Male	PL	10	143	166	1.66	1.93
10	Female	WL	12	111	132	1.41	1.68
11	Male	PL	8	155	164	1.64	1.73
12	Female	WL	2	73	102	0.71	1
13	Male	WL	4	130	143	1.25	1.37
14	Female	WL	3	68	82	0.89	1.08
15	Male	WL	2	111	152	1.32	1.8
16	Female	WL	10	80	110	1.11	1.53
17	Male	CF	10	114	125	1.4	1.54
18	Male	WL	2	152	152	1.11	1.11

Table 3.1: Participants strength training characteristics and barbell loads lifted during data collection. Possible competition types included powerlifting (PL), weightlifting (WL) or CrossFit (CF). Relative load represents the amount weight lifted divided by each participants' body mass (kg).

Participant ID	Neutral Lumbar Angle	Max Flexion Lumbar Angle	Flexion Range of Motion	Average Intervertebral Rotation Angle
1	-50.78	31.13	81.91	6.23
2	-46.32	6.91	53.23	1.38
3	-29.85	42.44	72.29	8.49
4	-34.33	37.59	71.91	7.52
5	-31.98	36.23	68.21	7.25
6	-22.66	64.71	87.36	12.94
7	-51.00	24.57	75.57	4.91
9	-38.60	33.23	71.83	6.65
10	-16.28	57.69	73.97	11.54
11	-39.49	33.58	73.07	6.72
12	-47.55	47.81	95.36	9.56
13	-29.27	34.20	63.47	6.84
14	-25.87	42.37	68.24	8.47
15	-27.18	51.61	78.79	10.32
16	-36.02	40.32	76.34	8.06
17	-36.73	28.30	65.02	5.66
18	-38.59	46.27	84.86	9.25

Table 3.2: Participant lumbar angle results during quiet standing (neutral) and the full trunk flexion task calculated using the planar kinematic lumbar spine model. All values are reported in degrees. Negative values represent the lordosis angle and positive values represent the angle of kyphosis during maximal flexion. Flexion range of motion was measured as the net change in angle between neutral and the maximal flexion values. Average intervertebral rotation angle values represent the average amount of rotation between each individual set of lumbar vertebrae at maximal flexion.

Variable	Deadlift	Squat	HHDL	LHDL	HBS	LBS
Peak Lumbar Flexion	9.4 ± 6.5	48.6 ± 5.5	8.6 ± 7.0	10.2 ± 6.5	47.8 ± 5.3	49.4 ± 6.4
Peak L4-L5 Moment	5.0 ± 3.5	51.8 ± 7.6	4.5 ± 3.8	5.5 ± 5.1	51.7 ± 8.1	51.9 ± 7.5
Peak L5-S1 Moment	4.8 ± 3.6	52.2 ± 7.6	4.1 ± 3.8	5.5 ± 5.0	52.4 ± 8.2	52.0 ± 7.7
Peak Compression Force	5.6 ± 4.5	50.5 ± 7.1	5.4 ± 6.1	5.8 ± 4.9	50.2 ± 7.4	50.7 ± 7.0
Peak Shear Force	5.0 ± 3.4	55.2 ± 9.4	4.7 ± 5.6	5.4 ± 3.3	53.6 ± 13.4	56.8 ± 9.2

Table 3.3: The time point at which each peak variable occurred during the lifting cycle for all conditions. Values presented as mean (±SD) lift cycle percentage with 0 representing the beginning of the lift cycle and 100 representing the end of the lift cycle.

3.2 Postural Differences within Squat and Deadlift Techniques

Results from the deadlift condition paired samples *t*-test revealed that at the time of peak L5-S1 moment during the lift cycle, there was a significantly greater shin angle, knee flexion angle and torso inclination angle during the LHDL technique in comparison to the HHDL technique, $p<.001$. Results from the squat condition paired samples t-test revealed that at the time of peak L5-S1 moment during the lift cycle, there was significantly greater torso inclination during the HBS technique in comparison to the LBS technique, $p<.01$. Mean (±SD) joint angle measurements for all lifting techniques, at the time of peak L5-S1 moment, are displayed in Table 3.3.

Joint / Segment	HHDL	LHDL	HBS	LBS
Shin Angle	9.8 ± 3.9	15.5 ± 4.1*	35.2 ± 6.3	34.3 ± 6.8
Knee Flexion Angle	47.7 ± 6.7	56.6 ± 8.5*	115.8 ± 11.2	115.2 ± 12.2
Hip Flexion Angle	81.9 ± 11.3	81.2 ± 12.4	98.4 ± 12.5	99.4 ± 12.1
Torso Inclination	21.7 ± 4.4	27.1 ± 4.6*	60.7 ± 4.1**	55.3 ± 5.1

Table 3.4: Mean (±SD) joint angles (degrees), measured at the time of peak L5-S1 moment, for the shin, knee, hip and torso. * indicates an angle significantly greater for the LHDL when compared to the HHDL (p<.001). ** indicates in angle significantly greater for the HBS when compared to the LBS (p<.001).

3.3 Lumbar Kinematics

Results from the factorial ANOVA revealed a main effect of lift condition where peak lumbar flexion was significantly greater during the deadlift condition (76.8 ± 16.1%) in comparison to the squat condition (64.2 ± 19.8%, Figure 3.1, $F(1,64) = 8.262$, $p = .005$). Planned paired samples t-tests displayed that within the deadlift condition, peak lumbar flexion was not significantly greater for the HHDL (78.2 ± 16.5%) when compared to the LHDL (75.3 ± 16.1% Figures 3.2 and 3.3, $t(16) = 5.4$, $p = .023$). Within the squat condition, there was significantly more lumbar flexion for the LBS (67.9 ± 19.6%) when compared to the HBS (60.4% ± 19.8%, Figures 3.4 and 3.5, $t(16) = -7.02$, $p<.001$).

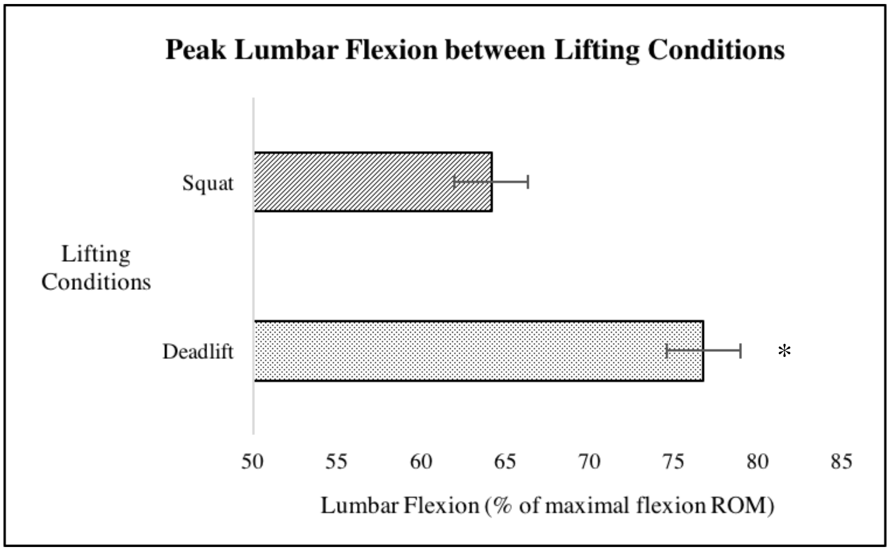

Figure 3.1: Peak lumbar flexion angle, represented as a percentage of maximal voluntary lumbar flexion ROM, during the deadlift and squat conditions. * Significantly greater than the squat condition (*p*=.005).

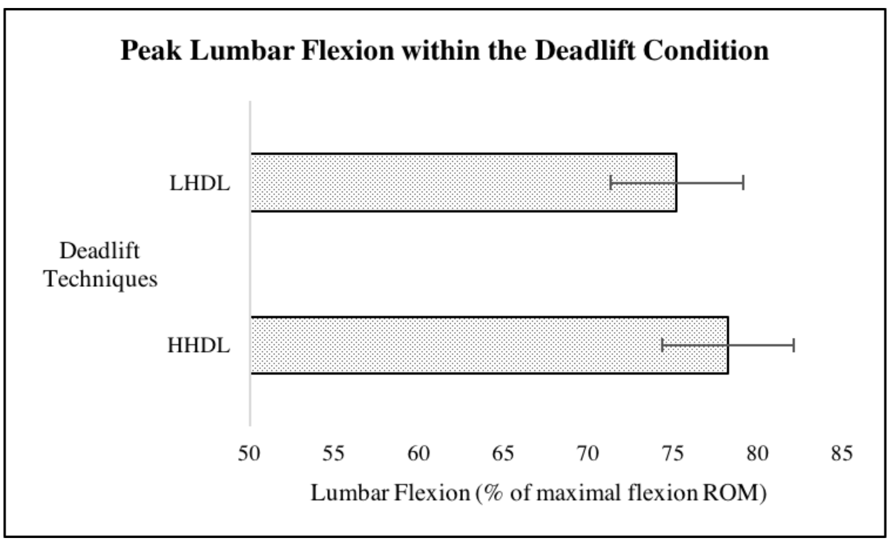

Figure 3.2: Peak lumbar flexion angle, represented as a percentage of maximal voluntary lumbar flexion ROM, during the LHDL and HHDL techniques.

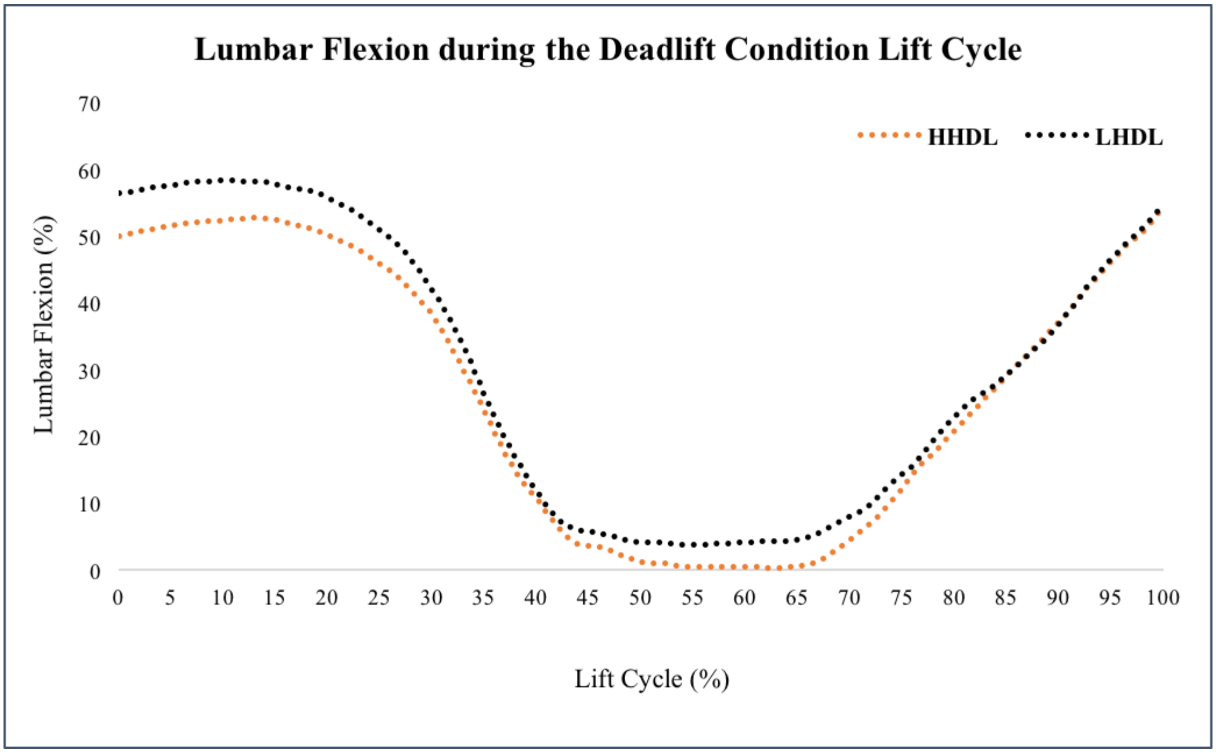

Figure 3.3: Lumbar flexion angle results from participant 7 throughout the entire lift cycle during the deadlift condition. Values represent the mean lumbar angle value obtained at each time point across all three lifting trials.

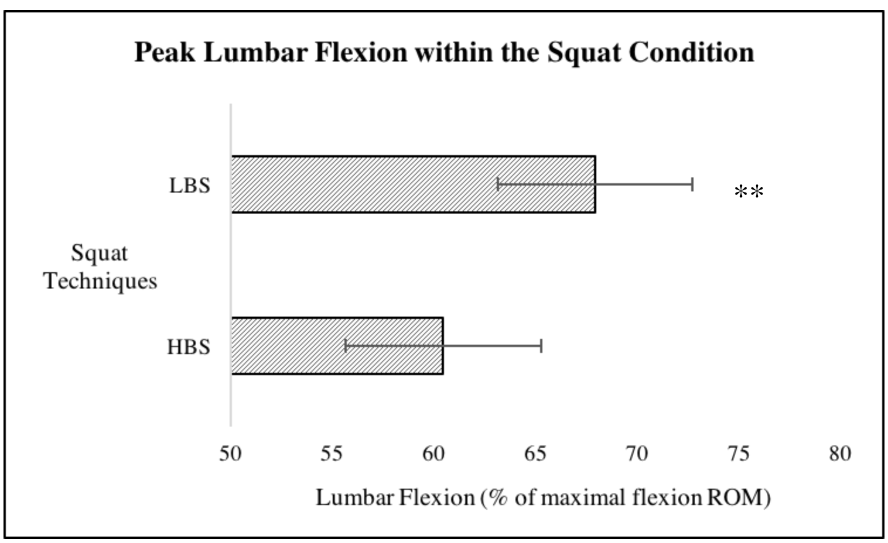

Figure 3.4: Peak lumbar flexion angle, represented as a percentage of maximal passive lumbar flexion ROM, during the LBS and HBS techniques. ** Significantly greater than the HBS (p<.001).

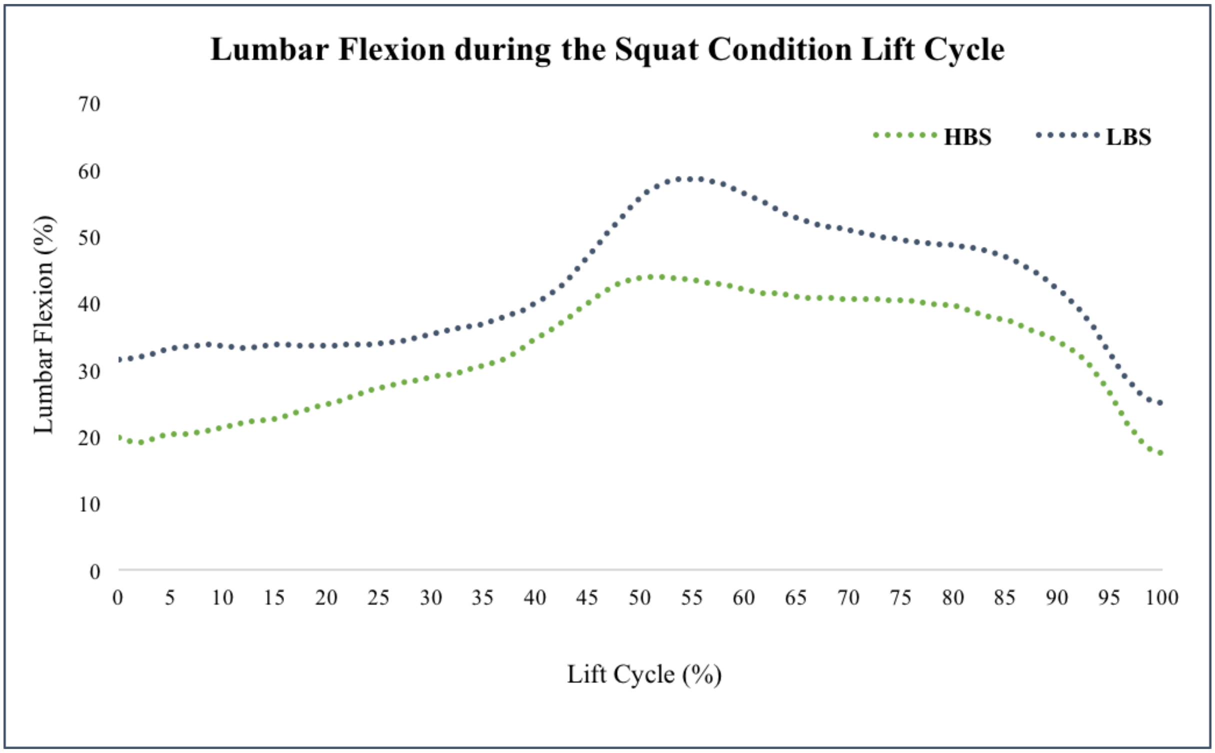

Figure 3.5: Lumbar spine angle results from participant 7 throughout the entire lift cycle during the squat condition. Values represent the mean spine angle value obtained at each time point across all three lifting trials.

3.4 Lumbar Kinetics

3.4.1 Average and Peak L4-L5 and L5-S1 Joint Moments

Results from the factorial ANOVA showed no significant differences between the deadlift and squat conditions for average L4-L5 and L5-S1 joint moments ($F(1,64) = .2$, $p = .657$; $F(1,64) = .395$, $p = .532$). Results from the planned paired comparisons within conditions revealed no significant differences in average L4-L5 ($t(16) = -2.36$, $p = .032$) or L5-S1 ($t(16) = -2.28$, $p = .037$) moments within the deadlift condition. Similarly, no significant differences in average L4-L5 ($t(16) = -0.86$, $p = .404$) or L5-S1 ($t(16) = -1.09$, $p = .290$) moments were seen within the squat condition. Refer to Table 3.4 for all between and within condition mean (±SD) values for all joint moment results.

Results from the factorial ANOVA showed no significant differences between the deadlift and squat conditions for peak L4-L5 ($F(1,64) = .895$, $p = .348$) and L5-S1 ($F(1,64) = 1.94$, $p = .168$) joint moments. Results from the planned paired comparisons revealed no significant differences in peak L4-L5 or L5-S1 moments within the deadlift condition, $t(16) = -0.69$, $p = .501$; $t(16) = -0.43$, $p = .671$ respectively. Similarly, no significant differences in peak L4-L5 or L5-S1 moments were seen within the squat condition, $t(16) = -0.95$, $p = .356$; $t(16) = -1.03$, $p = .391$ respectively.

Moment	**Deadlift**	**Squat**	**HHDL**	**LHDL**	**HBS**	**LBS**
L4-L5 Average	.089 ± .009	.090 ± .014	.088 ± .009	.089 ± .010	.089 ± .015	.090 ± .013
L4-L5 Peak	.130 ± .013	.126 ± .020	.130 ± .014	.130 ± .013	.125 ± .020	.127 ± .020
L5-S1 Average	.097 ± .010	.099 ± .014	.096 ± .009	.097 ± .010	.098 ± .015	.099 ± .013
L5-S1 Peak	.142 ± .013	.136 ± .020	.142 ± .014	.143 ± .013	.135 ± .020	.137 ± .021

Table 3.5: Mean (±SD) normalized joint moment values. Values were normalized to force magnitude (Newtons) and standing height (Meters) of each participant.

3.4.2 Average L5-S1 Compression and Shear Force

Results from the factorial ANOVA showed no significant differences for average compression force between the deadlift (3.84 ± 0.55) and squat (3.99 ± 0.72, Figure 3.6, $F(1,64) = .928$, $p = .339$). Results from the factorial ANOVA showed no significant differences for average shear force between the deadlift (2.00 ± 0.23) and squat (2.02 ± 0.29, Figure 3.7, $F(1,64) = .114$, $p = .736$).

Results from the deadlift planned paired comparisons revealed no significant differences for average compression force between the HHDL (3.82 ± 0.53) and LHDL (3.86 ± 0.57, Figure 3.8, $t(16) = -1.14$, $p = .273$). Results from the deadlift planned paired comparisons revealed significantly lower average shear force during the HHDL (1.98 ± 0.22) in comparison to the LHDL (2.02 ± 0.23, Figure 3.9, $t(16) = -3.33$, $p = .004$).

Results from the squat planned paired comparisons revealed no significant differences for average compression force between the HBS (3.92 ± 0.75) and LBS (4.06 ± 0.71, Figure 3.10, $t(16) = -2.08$, $p = .054$). Results from the squat within conditions paired sample *t*-test revealed no significant differences for average shear force between the HBS (2.04 ± 0.31) and LBS (2.01 ± 0.29, Figure 3.11, $t(16) = 1.51$, $p = .152$).

3.4.3 Peak L5-S1 Compression and Shear Force

Results from the factorial ANOVA showed no significant differences for peak compression force between the deadlift (5.78 ± 0.98) and squat (5.84 ± 1.15, Figure 3.6, $F(1,64) = .045$, $p = .833$). Results from the factorial ANOVA showed no significant differences for peak shear force between the deadlift (2.60 ± 0.38) and squat (2.53 ± 0.41, Figure 3.7, $F(1,64) = .442$, $p = .509$).

Results from the deadlift planned paired comparisons revealed no significant differences for peak compression force between the HHDL (5.79 ± 1.03) and LHDL (5.77 ± 0.97, Figure 3.8, $t(16) = 0.29$, $p = .777$). Results from the deadlift planned paired comparisons revealed no significant differences for peak shear force between the HHDL (2.57 ± 0.38) and LHDL (2.62 ± 0.38, Figure 3.9, $t(16) = -2.36$, $p = .031$).

Results from the squat planned paired comparisons revealed no significant differences for peak compression force between the HBS (5.71 ± 1.12) and LBS (5.96 ± 1.20, Figure 3.10, $t(16) = -2.55$, $p = .021$). Results from the squat planned paired comparisons revealed significant higher peak shear force during the HBS (2.59 ± 0.42) compared to the LBS (2.47 ± 0.40, Figure 3.11, $t(16) = 5.69$, $p<.001$).

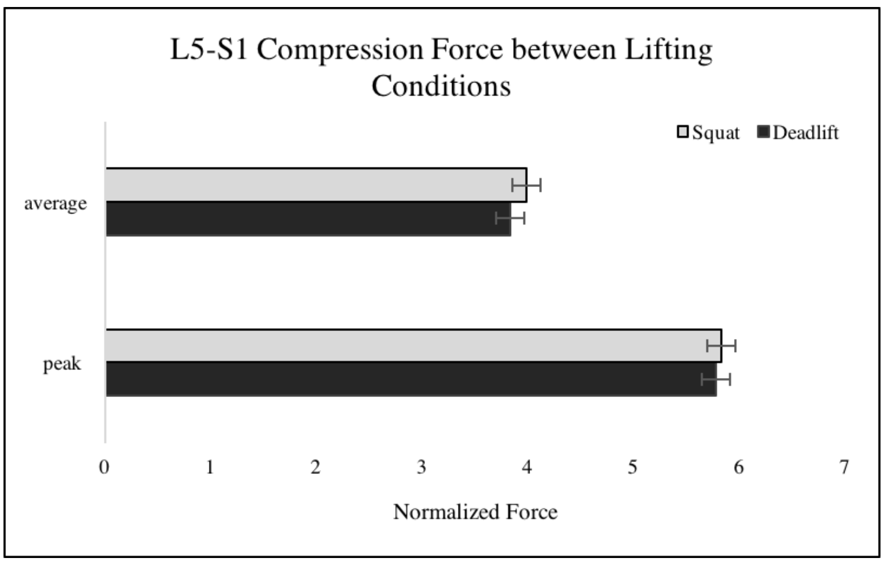

Figure 3.6: Peak and average normalized L5-S1 joint compression force between the deadlift and squat conditions. Values have been normalized to total external load (body mass + barbell load).

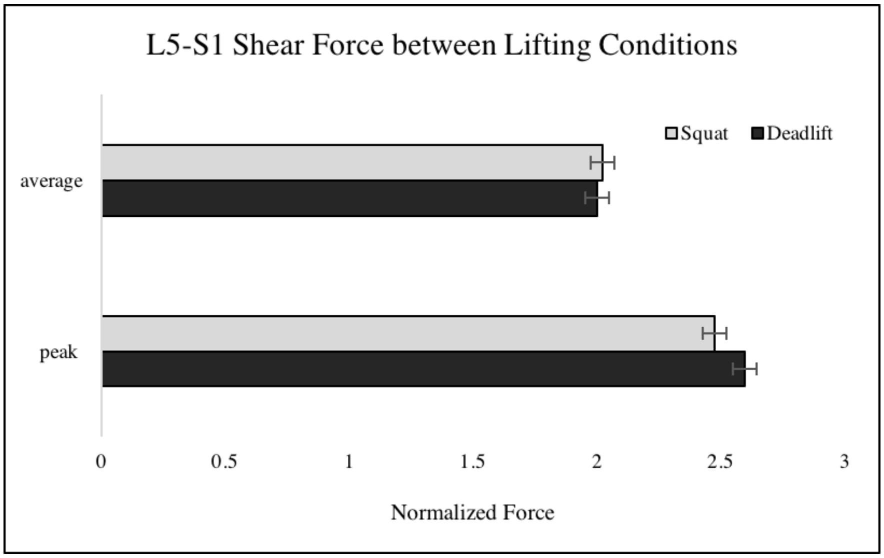

Figure 3.7: Peak and average normalized L5-S1 joint shear force between the deadlift and squat conditions. Values have been normalized to total external load (body mass + barbell load).

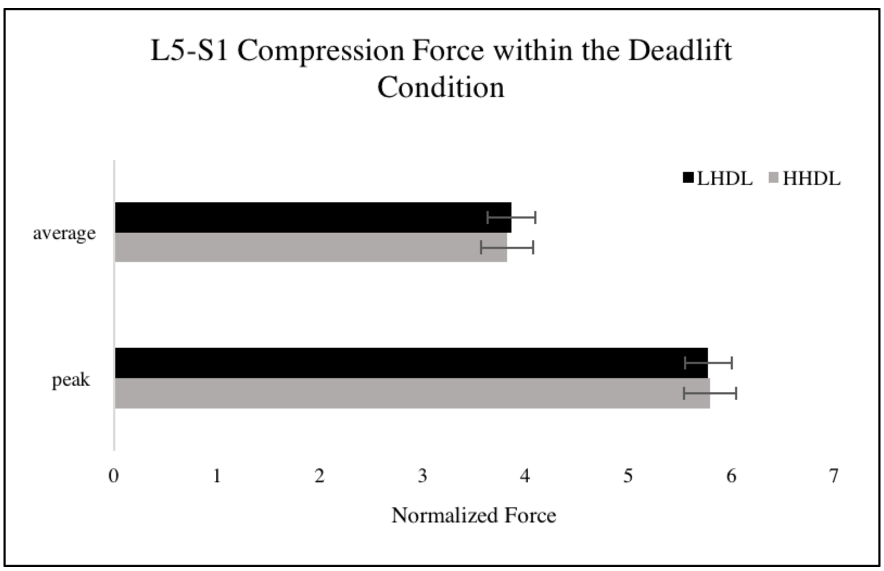

Figure 3.8: Peak and average normalized L5-S1 joint compression force during the LHDL and HHDL techniques. Values have been normalized to total external load (body mass + barbell load).

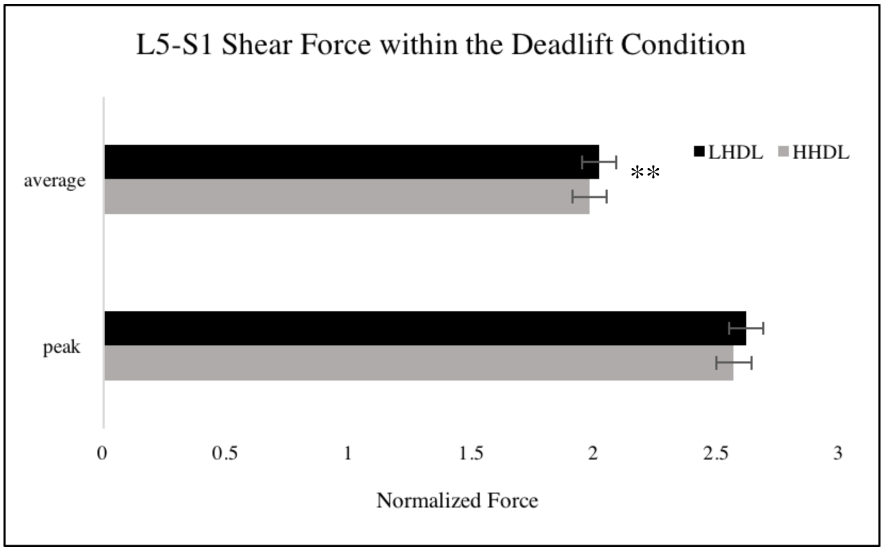

Figure 3.9: Peak and average normalized L5-S1 joint shear force during the LHDL and HHDL techniques. Values have been normalized to total external load (body mass + barbell load). ** Significantly greater than the HHDL (*p*=.004).

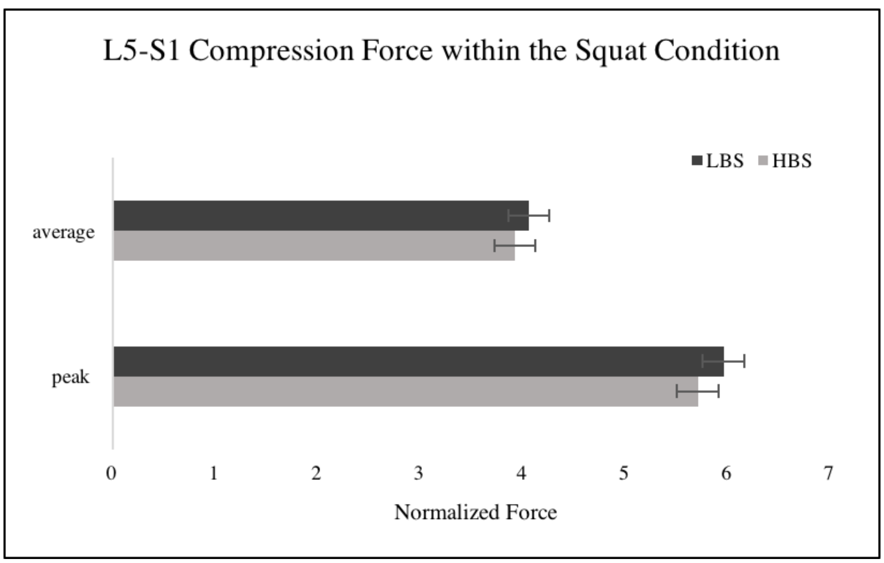

Figure 3.10: Peak and average normalized L5-S1 joint compression force during the LBS and HBS techniques. Values have been normalized to total external load (body mass + barbell load).

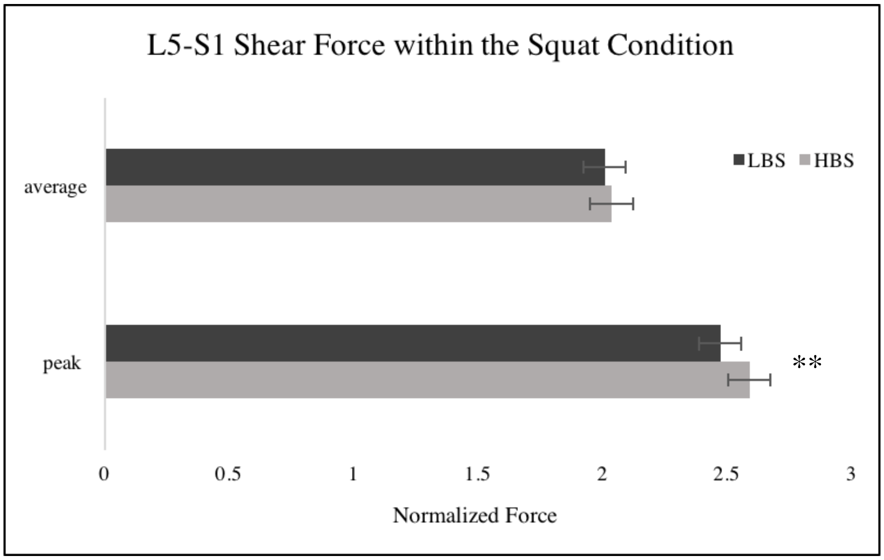

Figure 3.11: Peak and average normalized L5-S1 joint shear force during the LBS and HBS techniques. Values have been normalized to total external load (body mass + barbell load). ** Significantly greater than the LBS (p<.001).

3.5 Correlation between Hip Mobility and Lumbar Flexion

Results from the correlation analysis within the deadlift condition showed a non-significant negative correlation between maximum hip flexion ROM during the hip-hinge test and peak lumbar flexion taking place during the HHDL and LHDL techniques, Figure 3.12, $r(15) = -.40$, $p = .112$; $r(15) = -.43$, $p = .086$ respectively.

Results from the correlation analysis within the squat condition showed a non-significant negative correlation between maximum hip flexion ROM during the bodyweight deep squat and peak lumbar flexion taking place during the HBS and LBS techniques, Figure 3.13, $r(15) = -.44$, $p = .075$; $r(15) = -.44$, $p = .078$ respectively.

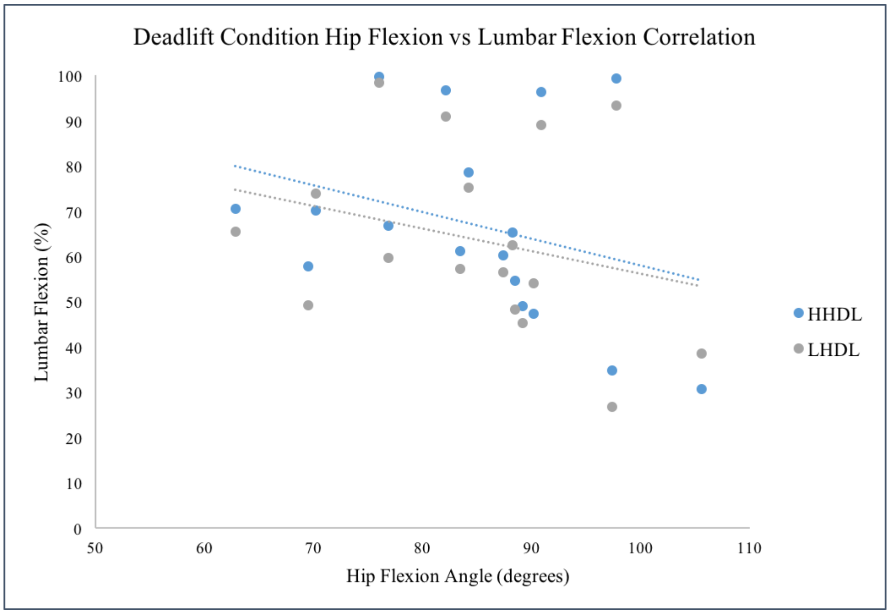

Figure 3.12: Scatter plot displaying the correlation between peak lumbar flexion values obtained during the deadlift trails and peak hip flexion values obtained during the hip hinge ROM trials. HHDL correlation value of R^2=-.40; LHDL correlation value of R^2=-.43

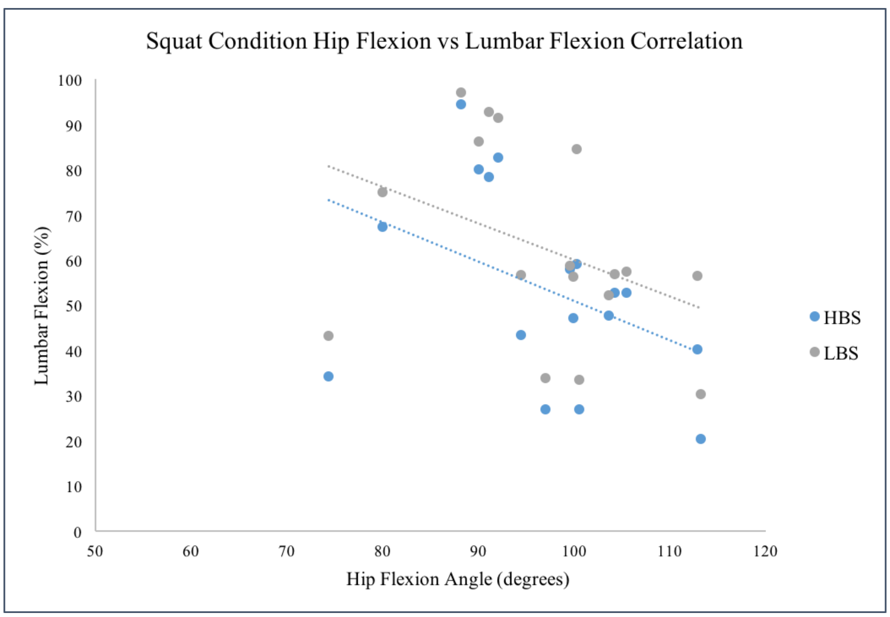

Figure 3.13: Scatter plot displaying the correlation between peak lumbar flexion values obtained during the squat trials and peal hip flexion values obtained during the bodyweight deep squat ROM trials. HBS correlation value of R^2=-.44; LBS correlation value of R^2=-.44

Chapter 4: Discussion

4.1 Hypotheses and Novel Findings

The primary purpose of this study was to compare two commonly used resistance training exercises (deadlift vs squat) as well as two technique variations within each exercise (HHDL vs LHDL and HBS vs LBS) for lumbar spine kinematic and kinetic variables related to performance and low back injury. The variables analyzed between and within lifts were peak lumbar flexion angle, low back moments (average and peak) and L5-S1 joint reaction force (average and peak).

The primary lumbar kinematics hypotheses were that between conditions, a greater peak lumbar flexion angle would be present in the deadlift condition when compared to the squat; while within conditions, HHDL and LBS techniques would result in greater peak lumbar flexion when compared to the LHDL and HBS. The findings support the between lifting conditions hypothesis as the deadlift condition had a significantly greater peak lumbar flexion angle compared to the squat. The within condition hypotheses were only partially supported as the LBS technique resulted in a significantly greater peak lumbar flexion angle compared to the HBS, while a less robust difference in lumbar flexion angle was found between the two deadlift variations (p=0.021).

The primary kinetic hypotheses were that between conditions, average and peak moments would be greater during the deadlift condition in comparison to the squat condition; while within conditions, average and peak moments would be greater during the LHDL and LBS when compared to the HHDL and HBS. In regards to L5-S1 compression and shear force compared between lifts, it was hypothesized that the deadlift would result in greater average and peak compression and shear force when compared to the squat; while within lifts, average and peak compression would be greater during the LHDL and HBS and shear would be greater during the HHDL and LBS. All low back moment hypotheses were not supported as no significant differences were observed between and within lifts. None of the L5-S1 compression and shear hypotheses were supported. Significant differences in peak shear force between HBS and LBS

The secondary hypothesis for the correlation between hip mobility range of motion and peak lumbar flexion angle was not supported. A negative relationship was present; however, the correlation was not statistically significant.

As previously presented in the review of current literature, this study is the first known to quantify and compare lumbar spine curvature relative to maximal lumbar flexion and L5-S1 joint reaction forces between the barbell deadlift and squat, as well as compare these measures between two common techniques utilized within each lifting condition.

4.2 Comparison and Interpretation of Results

4.2.1 Lumbar Kinematics

Lumbar kinematic results comparing the squat and deadlift indicate that while lifting submaximal loads at approximately 85% 1RM, peak lumbar flexion is greater during the barbell deadlift exercise in comparison to the squat (Figure 3.3). This finding is already anecdotally understood by health and fitness professionals; however, the magnitude of difference between lifts is less than one might expect as peak lumbar flexion, on average, was only 12.6% greater during the deadlift when compared to the squat at the same relative load (Figure 3.2).

Literature investigating lumbar spine kinematics during the barbell squat has presented results indicating that lumbar spine flexion increases during lift descent and this appears to share a relationship with torso angle (Campos et al., 2016; List et al., 2013; McKean et al., 2010). Lumbar spine angle results presented in the current study are not directly comparable to this literature due to lumbar angle measurement methodology incongruences. Results presented here indicate that lumbar spine angle moves away from neutral, to a more flexed position during squat descent (Figure 3.5); thus supporting the general kinematic pattern of the lumbar region during the squat that has been previously reported (Campos et al., 2017; McKean et al., 2010). Lumbar kinematic results from the current study also indicate that the lumbar spine undergoes significantly more flexion during the LBS technique in comparison to the HBS (Figure 3.4).

As torso inclination angle was significantly lower during the LBS and comparison to HBS (Table 3.3), this further validates the association between torso angle and lumbar flexion presented by Campos et al.; that being reduced torso inclination appears to occur as a result of increased lumbar spine flexion (Campos et al., 2017). Hip, torso and lumbar flexion angle results (Table 3.3; Figure 3.5) presented here offer evidence that past research investigating hip and torso kinematics during the barbell squat may have misinterpreted flexion at the lumbar spine as increased flexion at the hip joint, as methodology for measuring hip flexion was based upon the assumption that the torso remains rigid during a barbell squat (Escamilla et al., 2001).

Researchers investigating the barbell squat commonly define the torso segment by creating a vector between markers placed at the hip or pelvic region and the mid to upper thorax, shoulder or barbell itself (Escamilla et al., 2001; Legg et al., 2016; Wretenberg et al., 1996) and proceed to measure hip flexion based on the relative rotation between the thigh (knee to hip joint centres) and torso segments. This may cause flexion at the lumbar spine to be misreported as increases in hip flexion when changes in torso angle are present. Findings from the current study support this notion as at the time of peak L5-S1 moment, hip flexion angle (which was measured by the relative rotation between the thigh segment and pelvis) between the LBS and HBS was almost identical, yet the LBS had significantly greater lumbar flexion and less torso inclination. This indicates differences in torso angle, when controlling for squat depth, may occur due to changes in flexion at the lumbar spine and not the hip.

When comparing peak lumbar flexion angle between HHDL and LHDL techniques (Figure 3.4), results were approaching statistical significance; however, the difference in mean angle measurements between techniques was only 2.9%, indicating a relatively negligible effect on tissue loading (Adams et al., 1994). This indicates when completing a deadlift, one can choose to implement either technique without causing meaningful changes in the lumbar curvature.

Perhaps the largest novel contribution of the current study is the measurement of lumbar flexion angle taking place expressed relative to maximal in-vivo lumbar flexion ROM rather than an arbitrary angle value (Campos et al., 2016; List et al., 2013; McKean et al., 2010; Walsh et al., 2007). The average range of peak lumbar flexion taking place during barbell squats and deadlifts at 85% 1RM in the current study was 64% - 76% of maximal lumbar flexion ROM. This appears to be close to the ideal lumbar posture for optimal force distribution across the IVD. Adams et al. reported that optimal in-vitro compressive strength of the lumbar spine occurs between 0% - 75% of maximal flexion as compression in this range is entirely supported by the IVD; however, within this range, 50% of maximal flexion appears to be the optimal position for even force distribution across the posterior annulus, nucleus pulposus and anterior annulus of the disc (Adams et al., 1994). Lumbar flexion below 50% of maximal flexion causes greater force peaks in the posterior annulus, which over time can cause micro tears, weakening the posterior aspect of the disc and may lead to herniation when coupled with high degrees of lumbar flexion and compressive force (Adams et al., 1994; McGill, 1997). In comparison, flexion greater than 50% of the maximal range can cause a similar effect in the anterior aspect of the disc. Adams et al. also recognized that when comparing these ranges to in vivo conditions, optimal pressure distribution across the IVD is likely to occur around 80% of maximal lumbar flexion during in-vivo conditions. These findings were determined through measuring flexion angles at the individual vertebral level rather than global lumbar flexion, as was measured and reported in the current research. As a result, further investigation at the individual vertebral level is required to make definitive conclusions surround IVD loading. The global flexion value is simply providing a rough approximation of the amount of rotation taking place at each vertebral level; however, it is possible that the percentage of flexion taking place was not evenly distributed amongst all lumbar intervertebral joints.

Results presented here indicate that lumbar flexion seems unavoidable during these exercises and may occur at a range much greater than typically assumed by strength coaches and rehabilitation professionals. This, in combination with potential IVD force distribution inferences made based upon results presented by Adams et al. indicate that coaching one to complete a squat or deadlift with the lumbar spine as close to neutral as possible may be counterproductive. Rather, the primary concern should be around attempting to avoid large changes in lumbar curvature throughout the entire lift cycle. A better suited approach for attempting to avoid tissue breakdown the IVD may be to begin with the lumbar spine in the position of peak flexion one reaches during the lift (assuming this is less than 80% of maximum flexion) and attempting to maintain that same curvature during the entire lift, thus avoiding large changes in force distribution across the IVD. That being said, optimizing force distribution across the IVD may come at the expense of increasing risk of low back musculature strain, as this will result in a reduced moment arm length of the low back extensor musculature (van Dieen et al., 1999).

4.2.2 Lumbar Kinetics

No significant differences were observed between or within lifts for moments calculated at the L4-L5 and L5-S1 joints; however, significant differences in knee moments were observed between the HHDL and LHDL (results not reported). To the author's knowledge, this is the first study to compare L4-L5 or L5-S1 moment values between the barbell squat and deadlift exercises as well as the LHDL and HHDL techniques. This data supports that regardless of exercise selection and the technique variation used within that exercises, flexion moments generated at the two inferior most joints of the low back do not differ significantly when normalized to the amount of weight lifted. As individuals are typically capable of lifting higher loads during the deadlift exercise in comparison to the squat (Table 3.1), absolute flexion moment magnitude is greater during the deadlift exercise; however, this difference can be attributed to differences in the amount of load, not changes in the distance of that load from the joint centres.

Previous literature comparing the conventional deadlift to the sumo and HEX bar deadlift have indicated that the conventional technique results in significantly greater flexion moments at the L4-L5 joint and low back (Cholewicki et al., 1991; Swinton et al., 2011). This was said to occur due to changes in horizontal load distance from the joint centres (an increase in moment arm length during the conventional technique). When comparing the HHDL and LHDL conventional techniques, it appears the same effect does not occur. Although the load is positioned closer to the body during the HHDL position, this seems to be accompanied by a posterior shift in the position of the L4-L5 and L5-S1 joints, thus off-setting the theoretical reduction in moment arm length that should occur as a result of the change in bar placement.

Research comparing the HBS and LBS reported that hip flexion moments were significantly greater during the LBS technique in comparison to the HBS (Swinton et al., 2012, Wretenberg et al., 1996). Swinton et al. reported greater L5-S1 moments during the HBS in comparison to the LBS (Swinton et al., 2012). Neither of these findings were supported by results presented in the current research (Figure 3.7). This may be attributed to differences in study methodology. Some such differences include controlling for squat depth, utilizing different study designs (between vs within-subjects), and methodology for locating the anatomical position of the L5-S1 joint centre.

When expressed relative to bodyweight only, the current research found estimated peak L5-S1 joint reaction force to range between 4.1 – 14.5 (mean: 8.6 ± 2.7) times bodyweight for compression and 2.2 – 4.9 (mean: 3.5 ± 0.9) times bodyweight for shear during the barbell squat. The corresponding raw force value range was 3,079 N – 19,037 N (mean: 7,771 ± 4,296 N) for compression and 2,259 N – 5,768 N (mean: 3,161 ± 1,420 N) for shear. These estimates appear to be within the range of previously reported results in the range of 6,704-6,980 N for compression and 3,070-3,219 N for shear (Lander et al., 1986).

When expressed relative to bodyweight only, the current research found estimated peak L5-S1 joint reaction force to range between 5.0-13.5 (mean: 9.8 ± 2.6) times bodyweight for compression and 2.3-6.5 (mean: 4.4 ± 1.1) times bodyweight for shear during the barbell deadlift. The corresponding raw force value range was 3,718 N – 17,714 N (mean: 8,787 ± 4,288 N) for compression and 1,669 N – 5,510 N (mean: 3,851 ± 1,620 N) for shear. Average L4-L5 joint reaction compression and shear estimates during the deadlift (conventional or sumo) reported by Cholewicki et al. were 12,641 N and 1,739 N respectively for males and 6,400 N and 1,107 N respectively for females (Cholewicki et al., 1991). This was equal to 14.9 and 2.1 times bodyweight for males and 10.8 and 1.9 times bodyweight for females.

Results from the current study indicated that there is no significant difference in L5-S1 joint reaction force between the barbell deadlift and squat when normalized to load (Figure 3.6 and 3.7). Similar to conclusions made surrounding joint moments, the absolute magnitude of L5-S1 joint reaction is greater during the deadlift; however, this appears to be attributed to differences in barbell load magnitude rather than changes in load position or posture. Thus, if the barbell load remains consistent between a deadlift and squat exercise, it is estimated that the L5-S1 joint will bear approximately equal amounts of force during each lift.

When comparing L5-S1 joint reaction force estimates between the HHDL and LHDL, results suggest the one could use either conventional deadlift technique without significantly effecting the magnitude of peak L5-S1 joint reaction compression or shear force (Figure 3.8 and 3.9). Although small differences in peak lumbar flexion were observe between these techniques (Figure 3.3), this difference was not enough to alter joint reaction force.

When comparing L5-S1 joint reaction force estimates between the HBS and LBS, results suggest that while there is not a significant difference in compression force between squat techniques (Figure 3.10), there is significantly greater shear force experienced at the L5-S1 joint during the HBS technique (Figure 3.11). This appears to be a result of decreased lumbar flexion during the HBS technique at the time of peak L5-S1 moment, resulting in back extensor musculature orientation being more perpendicular relative to the horizontal plane of the spinal column, thus creating a larger shear force component. This finding is important for several reasons. Ergonomics literature has recognized peak joint shear force as being a strong predictor of self-reported low back pain within manual labor industries (Norman et al., 1998). Greater peak shear force values during the lifting technique with more torso inclination is opposite to what one might conclude if the only the effects of load force on the joint were considered while neglecting musculature force contributions. This is due to the back extensor musculature generating majority of the peak shear force experienced at the L5-S1 joint during the barbell back squat. As a result, small alterations in torso angle (as seen between the HBS and LBS) creates negligible changes in load shear force; while subtle changes in lumbar flexion can create large differences in muscle force due to the corresponding changes musculature line of pull relative to the joint. As a result, less joint shear force is present during the LBS due to greater lumbar flexion, causing the low back musculature line of action to run more parallel to the spine. This emphasizes the importance of measuring joint reaction force rather than simply load force when drawing implications surrounding how resistance training exercises may contribute to joint loading.

Out of all previously mentioned studies that reported joint compression and shear force estimates during the barbell squat or deadlift exercise, the current study is the only one to utilize a model that accounted for changes in single-equivalent muscle (SEM) moment arm length and line of pull with respect to changes in lumbar flexion angle. Results indicate this is critical for accurate force estimates during the deadlift and squat exercise as no significant differences in L5-S1 joint moments were observed between conditions; however, significant differences in joint compression and shear occurred. Musculoskeletal models assuming static low back musculature moment arm length and line of pull relative to the lumbar joints would have produced similar L5-S1 force estimates across all conditions as they do not account for the effects of changing lumbar curvature on joint reaction force, which was shown to be significant when comparing the HBS and LBS (Figure 3.11).

4.2.3 Hip Mobility Considerations and Pelvic Movement

Results comparing the relationship between individual hip flexion ROM and peak lumbar flexion angle indicated that although a negative relationship was present between hip and lumbar flexion, the relationship was not significant; thus indicating there are additional variables contributing to lumbar flexion during these exercises. It is a common belief in the fitness industry that limited hip flexion ROM will lead to greater flexion at the lumbar spine, as barbell deadlifts and squats require large amounts of flexion at the hip joint (Escamilla et al., 2000; Escamilla et al., 2001). Correlation analysis results (Figure 3.12) partially support this as the two factors do share a relationship; however, other factors may be stronger predictors of lumbar flexion during parallel barbell back squats and deadlift.

Another common occurrence during the barbell squat is pelvic movement at peak decent in which the lumbo-sacral region appears to tuck inwards, referred to in weightlifting jargon as “butt wink”. Although it was not the primary purpose of the present research to analyze butt wink, the results provide modest insight into the kinematics of this movement. When comparing changes in lumbar flexion (Figure 3.2) to pelvic tilt (Figure 6.1) during the squat, the pelvic tilt curve is much steeper at peak squat decent, indicating a more sudden change in position in comparison to the lumbar curvature. This indicates that butt wink appears to be predominantly pelvic movement and does not necessarily create large increases in flexion throughout the entire lumbar region. Further analysis is needed on this topic to analyze how butt wink specifically may affect loading across the L5-S1 joint in order to determine potential low back injury implications.

4.3 Limitations and Future Research

Accurately measuring in vivo loads at the lumbar joints is very difficult; however, musculoskeletal modeling is currently the most feasible approach to obtain in vivo load estimates. Modeling approaches vary in complexity based on the number of assumptions. While the modeling approach implemented in this study was relatively complex, the accuracy of the load estimates calculated are still limited by several assumptions. As noted by Reeves and Cholewicki in their review on modeling of the lumbar spine, the equilibrium approach used in this study does not account for changes in muscular contraction as a result of alterations in vertical load position (Reeves & Cholewicki, 2003). The equilibrium approach utilized assumed that all muscle force contributions were created by the back extensor musculature and neglected the effects of co-contraction. As muscular co-contraction patterns may change with altered spinal column stability demands, this would directly influence joint reaction force estimates (Granata et al., 2001). As a result, using an equilibrium approach to compare spinal loading between the squat and deadlift exercises may potentially underestimate joint reaction forces during the squat exercise given the large difference in vertical bar position, theoretically increasing stability demands. The counter argument could also be made that using a lumbar spine model, which accounts for stability demands may only be critical during low load lifting activities, as lifting near maximal loads seems to result in maximal contraction of the core and back extensor musculature regardless of load position. This being supported by findings displaying the relationship between increased stiffness in the spine and decreased reliance on proprioceptive feedback as a result of high loads (Gardner-Morse et al., 1995; Hamlyn et al., 2007; Stokes et al., 2000).

There are also considerable limitations to using a SEM approach to estimating the magnitude and direction of force created by all the musculature spanning the lumbar joints. There has been much debate within the literature as to what must be considered when creating an accurate SEM model to estimate lumbar joint loading. Some models only consider local musculature within the lumbar region where as others consider all muscles spanning the lumbar joint (Macintosh et al., 1993; van Dieen et al., 1999). Furthermore, McGill has recognized that the contribution from each specific muscle group contained within the SEM model may change based on lumbar posture (McGill, 2000). There is also debate surrounding the ability of intra-abdominal pressure (IAP) to create lumbar decompression, although it appears any decompressive force created by IAP is offset by the compressive penalty of the increased core musculature contraction required to generate IAP in the first place (Reeves et al., 2003). In addition, the van Dieen model was not intended to be used within a competitive strength athlete population. As these athletes typically have greater muscle mass within the back extensors due to hypertrophy as a result of prolonged training, this could affect the SEM model. As increases in individual muscle cross-sectional area would influence the relative force contribution of each muscle contained within the model, this would affect the estimated moment arm lengths and line of action within the SEM model. Current advances in musculoskeletal modeling using simulation software such as OpenSim (Delp et al., 2007) may provide an approach to more accurately measure muscular forces given the programs ability to estimate joint reaction forces using a variety of highly detailed muscular models (Christophy et al., 2012; Raabe et al., 2016; Senteler et al., 2016).

Using markers placed on the surface of the skin to drive the relative positioning of the lumbar spine model could potentially increase error in the angle measurements. As competitive strength athletes have large back extensor musculature, this could have created greater amounts of skin displacement during trunk flexion. This would influence lumbar angle measurements as the lumbar markers could undergo greater movement as a result of skin displacement rather than lumbar vertebral displacement only.

Modeling lumbar kinematics requires an accurate understanding of how each lumbar vertebrae rotates relative to one another during torso flexion. The relative distribution of lumbar vertebrae rotation for the model used in this study were based upon radiographic images taken of lumbar spine displacement during a bodyweight torso flexion task (Wong et al., 2006). It is possible that the relative distribution of rotation across the lumbar spine may change under high load movements, such as heavy barbell squats and deadlifts. Furthermore, representing flexion as a percentage of maximum flexion ROM can also have limited implications when comparing findings to other research as maximal flexion ROM is task dependent. As a result, the task used to measure maximum lumbar ROM in the current research may have been considerably less than those used within ergonomics literature. So while the results reported may seem high, they may still be considerably less than what is required to reach maximal tissue tolerance limits.

The current research measured and reported an estimate of global lumbar spine flexion taking place during the barbell deadlift and squat, not flexion at the intervertebral joint level. In order to directly infer loading across different tissues at the FSU, the exact relative rotation between the inferior and superior vertebra at the specific lumbar joint is required. As a result, caution should be taken when inferring individual tissue loading at the FSU from a measurement of global lumbar flexion.

The population studied may limit the application of these findings specifically to experienced weightlifters. Novice weightlifters or individuals who engage in recreational resistance training could potentially exhibit different movement patterns. It requires a high level of motor control for one to demonstrate the ability to flex at the hips and/or lumbar spine completely independently of one another. This is a level majority of competitive lifters have achieved. As such, recreational and novice lifters may exhibit greater amounts of lumbar flexion during the barbell squat and deadlift at submaximal loads due to motor control deficiencies. As a result, it is important to further analyze lumbar spine kinematics and kinetics across a variety of populations.

Allowing participants to self-report their one repetition maximum (1RM) for each lift presents another limitation to this research. Although competitive strength athletes are usually able to accurately predict their 1RM, it is possible that some participants used loads that were above or below 85% of their 1RM. This could be attributed to the within lift technique variations potentially altering maximal strength as well as the strength decrease present when not wearing a weightlifting belt. Utilizing a within subject's design helped control for potential differences in load between participants; however, load differences may have caused a larger variance within the collected data.

Further research is required in order to more accurately define how heavy barbell squats and deadlifts lead to low back injury. It would be advantageous to conduct a study using radiographic imaging techniques to measure lumbar kinematics for improved accuracy of lumbar vertebrae rotational displacement during heavy barbell squats.

The issue of ideal lumbar posture for preventing damage at FSU during heavy squats and deadlifts appears to be an optimization problem between force magnitude and relative distribution across the IVD. If all other variables are held constant, absolute magnitude of force placed upon the FSU increases with greater lumbar flexion due to reduction in musculature moment arm lengths; however, this is accompanied with increased force distribution across the entire IVD. The magnitude of sensitivity between these factors will help establish if the significant differences in lumbar flexion between squats, deadlifts, and the techniques within them create differences in IVD injury risk. To further complicate the situation, the FSU as a whole can undergo physiological changes in response to different external conditions (McGill & Brown, 1992; McGill, 1997; Neubert et al., 2014). As a result, the optimization between absolute force magnitude and distribution at the IVD and its relativity to amount of lumbar flexion, could be individual specific.

Further investigation into the spinal columns primary strategy to prevent vertebral translation when exposed to high shear load force is to increase compression, generate off-setting shear forces, or create an optimal balance between the two.

Chapter 5: Summary and Conclusions

5.1 Summary

Findings presented within this thesis describe and compare the kinematic response of the lumbar region to submaximal barbell squat and deadlift exercises and technique variations. It also presents the estimated joint moments at the L4-L5 and L5-S1 level and L5-S1 joint reaction forces during such tasks. These results present objective data surrounding the kinematic and kinetic differences at the lumbar spine and L5-S1 joint during specific heavy lifting tasks and techniques within a well-trained population. This data can provide a foundation for others to analyze the resulting effect of such demands on load distribution across the FSU components and then estimate tissue response over time, thus formulating an understanding of how exactly injury may occur during these exercises in order to develop effective injury prevention strategies.

5.2 Conclusions

When completing a barbell deadlift or squat at a load of approximately 85% 1RM, the lumbar spine undergoes considerable amounts of flexion during both exercises. Furthermore, one is likely to experience more lumbar flexion if they use a LBS technique in comparison to a HBS technique. During the deadlift exercise, using a HHDL technique does not appear to significantly increase peak lumbar flexion in comparison to the LHDL technique.

Although the barbell deadlift is commonly thought to be a more stressful lift for the low back in comparison to the squat, it appears that these lifts create similar magnitudes of L5-S1 joint reaction force if barbell load is matched between lifts. Similarly, employing either a HHDL or LHDL technique to complete a barbell deadlift does not appear to significantly affect the magnitude of L5-S1 joint loading. During the barbell squat however, using a LBS technique appears to result in significantly less peak L5-S1 joint shear force. Although significant from a statistical perspective, further research is required to determine if this difference in force magnitude is large enough to effect tissue damage, subsequently leading to low back injury.

Using a dynamic SEM model to estimate the force contribution from the back extensor musculature is required to accurately estimate joint reaction forces in the lumbar spine during the barbell deadlift and squat. A static SEM model that does not adjust muscle moment arm length and line of action in response to changes in lumbar flexion lacks the sensitivity required to accurately evaluate how different deadlift and squat techniques influence joint reaction force.

Ideal posture for low back safety during these exercises needs to be further evaluated. While current practice places an emphasis on simply avoiding near maximal lumbar flexion, this constitutes too large of a range to be considered ideal for low back safety. Results presented here display that a 7% change in lumbar flexion can significantly change peak L5-S1 shear joint reaction force estimates. As such, investigation into what amount of flexion is ideal for even force distribution across the FSU, and if one can maintain this posture throughout the entire lift cycle in order to avoid potential negative consequences associated with lumbar spine movement under extremely high loading conditions.

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Appendices

Appendix A – Participant Recruitment Flyer

Competitive Powerlifting, Weightlifting and CrossFit Athletes needed for a research study

Who

You are eligible to participate in this research study if:

- You are between the ages of 18 – 55.
- You have competed in a weightlifting, powerlifting or CrossFit competition within the past year.
- You are experienced and comfortable performing both high-bar and low-bar squat techniques.
- You have not had a major injury that has caused you to significantly alter your training within the past 6 months.
- You do not have a clinically diagnosed spinal deformity (eg. Scoliosis).

What

As a participant in this study, you will be required to:

- Attend a single data collection session approximately 2 hours in length.
- Have non-invasive markers and sensors attached to several locations on your body for the purpose of tracking body movement and muscle activity.
- Complete a total of 12 lifts consisting of various deadlift and squat techniques at a sub-maximal load.
- Refrain from doing any heavy lower body resistance training sessions for 48 hours prior to your testing session.

Where

All testing will take place in the Biomechanics of Balance and Movement lab, located on the third floor of the Physical Activity Complex (PAC) at the University of Saskatchewan. The PAC is located at 87 Campus Drive, Saskatoon, SK.

When

You may schedule your testing session between the dates of November 5th – 10th or 19th – 27th.

Why

This study is being conducted by researchers at the University of Saskatchewan to investigate the forces created in the low back during different deadlift and squat techniques. You will not receive monetary compensation for participating in this study; however, you will receive a document with your personal results and its significance. This study has been approved by the Biomedical Research Ethics Board at the University of Saskatchewan.

How

Contact Corey Edington (contact info attached to the bottom of this poster) if you would like to participate. If you have any further questions, please contact Joel Lanovaz by email (joel.lanovaz@usask.ca) or phone (306-966-1073). Joel Lanozav is the principal investigator of this study and a faculty member at the College of Kinesiology.

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Appendix B – Participant Consent Form

UNIVERSITY OF SASKATCHEWAN

PARTICIPANT INFORMATION AND CONSENT FORM

The effects of deadlift and squat posture on lumbar kinetics and kinematics

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INTRODUCTION

You are invited to take part in a research study because you have experience performing the deadlift and squat exercises with heavy loads.

Your participation is voluntary. It is up to you to decide whether or not you wish to take part. If you wish to participate, you will be asked to sign this form. If you do decide to take part in this study, you are still free to withdraw at any time and without giving any reasons for your decision.

Please take time to read the following information carefully. You can ask the researcher to explain any words or information that you do not clearly understand. You may ask as many questions as you need. Please feel free to discuss this with your family, friends or family physician before you decide.

WHY IS THIS STUDY BEING DONE?

This research study is looking at how different deadlifts and squats change the loads on the lower back. Heavy deadlifts and squats can create high forces that place stress on the low back. In order to help reduce the risk of low back injury during weight training, it is important that we understand how different lifts change the loads in the low back. In this study we will be looking at two different styles of deadlifts and two different styles of squat lifts. The styles we are looking at have different postures. For the deadlift we are looking at powerlifting style compared to an Olympic lifting style. For the squat, we are looking at a high-bar and a low-bar position. The information from this study will help the researchers understand how deadlifts, squats and different postures alter low back loads and may lead to improvements in training and lifting techniques in the future.

WHO IS CONDUCTING THIS STUDY?

This study is being conducted by faculty members and a graduate student within the School of Physical Therapy and College of Kinesiology at the University of Saskatchewan. The researchers and the University of Saskatchewan are not being paid to conduct this study.

WHO CAN PARTICIPATE IN THE STUDY?

You are eligible to participate in this study if you are between the ages of 18 to 55 and have taken part in a powerlifting or Olympic weightlifting competition within the past year. In addition to this, you must be experienced and comfortable performing both the high-bar and low-bar squat technique. If you have had a significant injury within the past 6 months, you are not eligible to participate in this study. A significant injury is an injury that has caused you to stop or make major changes to your regular training schedule for greater than two weeks. If you have a diagnosed spinal deformity (eg. Scoliosis) you cannot participate in this research study.

You must be comfortable wearing compression clothing. For this study, you will be asked to wear compression shorts if male, and compression shorts and a sports bra if female. This is required for accurate data collection. You will not be able to wear any supportive equipment, such as a weightlifting belt.

After first receiving this form, you will have one week to schedule a time for testing. If no response is given within one week you will not be able to participate in this research study.

WHAT DOES THE STUDY INVOLVE?

All data collection will take place during one single testing session lasting approximately 90 minutes. We ask that you refrain from doing any heavy resistance training sessions for 48 hours prior to your scheduled testing session. Please bring appropriate compression clothing as outlined in the previous section. You will be completing all lifts in socks that will be provided to you by the researcher. Upon arrival at the Physical Activity Complex at the University of Saskatchewan, you will proceed to the Biomechanics of Balance and Movement lab in room 355 located on the third floor. You will then progress through the following phases of the testing session:

i) Informed Consent – You will be required to read and sign this consent form. A copy of this consent form will be provided for you by the researcher upon arrival.
ii) Initial measurements – Age, weight, height, arm span, and self-reported deadlift and squat one repetition max will be recorded.
iii) Landmarking – The researcher will identify specific bony locations on the body by pressing on the skin surface in different locations. These location include the feet, knees, and spine. Once the location is identified, a small mark will be placed on the skin in that location using a special skin-safe washable marker.
iv) Warm-up – You will be required to wear a wireless heart rate monitor for the full duration of the warm-up. You will be given approximately 15 minutes to complete your own mobility warm-up. This can include foam rolling, stretching, and any other low intensity activities. After this, you will be required to complete a testing specific warm-up. This will consist of two sets of four deadlifts using each posture and two sets of four squats using each posture. The amount of weight lifted for these warm-up deadlifts and squats will be 65% of your self-reported one repetition maximum. The researchers may instruct you to make any necessary adjustments if your lifting posture variations are not within the standardized guidelines. The warm-up will be supervised by one of the researchers and a researcher with a Certified Exercise Physiologist accreditation will be present (CEP).

v) Testing

a. Set-up - Sensors which record the activity of your muscles will be placed on several locations on your back and legs. These sensors are adhesive pads that only record information. The locations of these sensors may be shaved to remove any hair and cleaned using a small alcohol wipe. You will also have special small reflective spheres attached to various spots on your legs, body and arms using non-allergenic two-sided tape. These spheres are recorded by special cameras in the lab and allow us to track your movement. Removal of the muscle activity sensors and reflective spheres after the study is similar to taking off a band-aide.
b. Mobility and Lifting Trials - The mobility trials will consist of two torso flexion, hip-hinge, and hip-rockback movements. For the torso flexion, you will be asked to bend forward and down through your upper body as far as possible from a standing position without moving at the hips or knees. For the hip-hinge movement, you will be instructed to slightly flex your knees (so the legs are straight but knees are not locked) then maximally flex forward at your hips from a standing position. For the hip-rockback movement, you will be asked to assume a 4-point (hands and knees) position on the floor and be then move your hips backward as close to your heels as possible.

The lifting trials will consist of three sets of a single lift for each exercise (deadlift and squat) and posture (traditional and powerlifting), for a total of twelve individual lifts. For the deadlift exercise, you will be required to vertically lift a loaded bar weighing 85% of your one repetition maximum from its resting position to a height just below hip level when standing. For the squat exercise, you will be required to support a bar weighing 85% of your one repetition maximum behind your head and across your shoulders (as per usual squat technique). You then must lower the bar from a standing position using a squat movement until your upper legs are parallel with the floor, then immediately raise the bar back to the starting position. You will know you have reached the parallel position when your tailbone makes contact with a rubber string, which will be positioned before the squat. Posture will be altered during both lifts by slightly changing the position of the bar at the beginning of each lift. The order in which you complete each lift will be randomly determined at the beginning of the testing session. You will be given a rest time of two minutes between each lifting trial.

vi) Cool-down (optional) – You will complete a cool-down consisting of a 10 minute stationary bike and/or static stretching.

Each lift will be recorded using digital video and photographs will be taken. This is required during the analysis process. The raw video and photographs will only be viewed by the researchers. If you do not agree to be video recorded, you will not be able to participate in this study.

WHAT ARE THE BENEFITS OF PARTICIPATING IN THIS STUDY?
If you choose to participate in this study, there will be no direct benefit to you. It is hoped the information gained from this study will help rehabilitation, strength and conditioning, biomechanics and ergonomics professionals to understand how different lifting styles can effect injury risks in the low back when lifting very heavy loads. It will also provide direction for future research in this area.

ARE THERE POSSIBLE RISKS AND DISCOMFORTS?

If you choose to participate in this study, you will be exposed to risks associated with performing heavy resistance training. These risks include:

- *Acute muscle and/or joint injury*
- *Cardiovascular risks associated with short-term elevations in blood pressure and heart rate*
- *Dizziness*

Additionally, the adhesive tape used to attach the reflective markers and EMG sensors may cause very mild, temporary skin irritation in some participants when they are removed. If there is some skin itching or redness, it usually disappears in 24 hours.

WHAT HAPPENS IF I DECIDE TO WITHDRAW?
Your participation in this research is voluntary. You may withdraw from this study at any time. You do not have to provide a reason. There will be no penalty or loss of benefits if you choose to withdraw. Your future academic status and/or relationships with the University of Saskatchewan will not be affected

If you choose to enter the study and then decide to withdraw later, all data collected about you during your enrolment will be retained for analysis.

WILL I BE INFORMED OF THE RESULTS OF THE STUDY?
The results of the study will be provided to you approximately 6-8 weeks after your data collection session. Each participant will be sent their own personal results document via email. The email will contain their personal data from all outcome measures along with a brief explanation of each variable. The document will also summarize initial group findings from the research and the implications for real-world application. All group findings will be presented as aggregate information, so your identity will never be disclosed

WHAT WILL THE STUDY COST ME?
You will not be charged for any research-related procedures. You will not be paid for participating in this study. You will not receive any compensation, or financial benefits for being in this study, or as a result of data obtained from research conducted under this study.

WHAT HAPPENS IF SOMETHING GOES WRONG?

In the case of any medical emergency that may arise during testing, trained staff and emergency protocols will be in-place to ensure immediate professional response to the situation. Necessary medical treatment will be made available at no cost to you. By signing this document, you do not waive any of your legal rights.

WILL MY TAKING PART IN THIS STUDY BE KEPT CONFIDENTIAL?

Your confidentiality will be respected. No information that discloses your identity will be released or published without your specific consent to the disclosure. However, research records identifying you may be inspected in the presence of the Investigator or his or her designate by representatives from the University of Saskatchewan Research Ethics Board for the purpose of monitoring the research. However, no records, which identify you by name or initials, will be allowed to leave the Investigators' offices.

All paper documents containing any personal information will be stored in a locked filling cabinet in the principal investigators office. After five years, these documents will be destroyed using confidential shredding. All digital files containing personal information, including video/photographs, will be stored on a password protected computer located in the principal investigators office. After five years, these files will be permanently deleted.

The results of this study may be presented in a scientific meeting or published, but your identity will not be disclosed. Any identifying characteristics in any video or still pictures used in any presentations will be concealed to maintain your anonymity.

WHO DO I CONTACT IF I HAVE QUESTIONS ABOUT THE STUDY?

If you have any questions or desire further information about this study before or during participation, you can contact *Corey Edington by email at corey.edington@usask.ca*. You may also contact the principal investigator and College of Kinesiology faculty member, Joel Lanovaz, by email (joel.lanovaz@usask.ca) or phone (306-966-1073).

If you have any concerns about your rights as a research participant and/or your experiences while participating in this study, contact the Chair of the University of Saskatchewan Research Ethics Board, at 306-966-2975(out of town calls 1-888-966-2975). The Research Ethics Board is a group of individuals (scientists, physicians, ethicists, lawyers and members of the community) that provide an independent review of human research studies. This study has been reviewed and approved on ethical grounds by the University of Saskatchewan Research Ethics Board.

CONSENT TO PARTICIPATE

Study Title: The effects of deadlift and squat posture on lumbar kinetics and kinematics

- I have read the information in this consent form.
- I understand the purpose and procedures and the possible risks and benefits of the study.
- I was given sufficient time to think about it.
- I had the opportunity to ask questions and have received satisfactory answers.
- I understand that I am free to withdraw from this study at any time for any reason and the decision to stop taking part will not affect my future relationships.
- I give permission to the use and disclosure of my de-identified information collected for the research purposes described in this form.
- I understand that by signing this document I do not waive any of my legal rights.
- I will be given a signed copy of this consent form.
- By singing this form, I agree that videos and photographs can be taken during participation in this study.

I agree to participate in this study:

Printed name of participant:	Signature	Date
Printed name of person obtaining consent:	Signature	Date

Appendix C – Supplementary figures

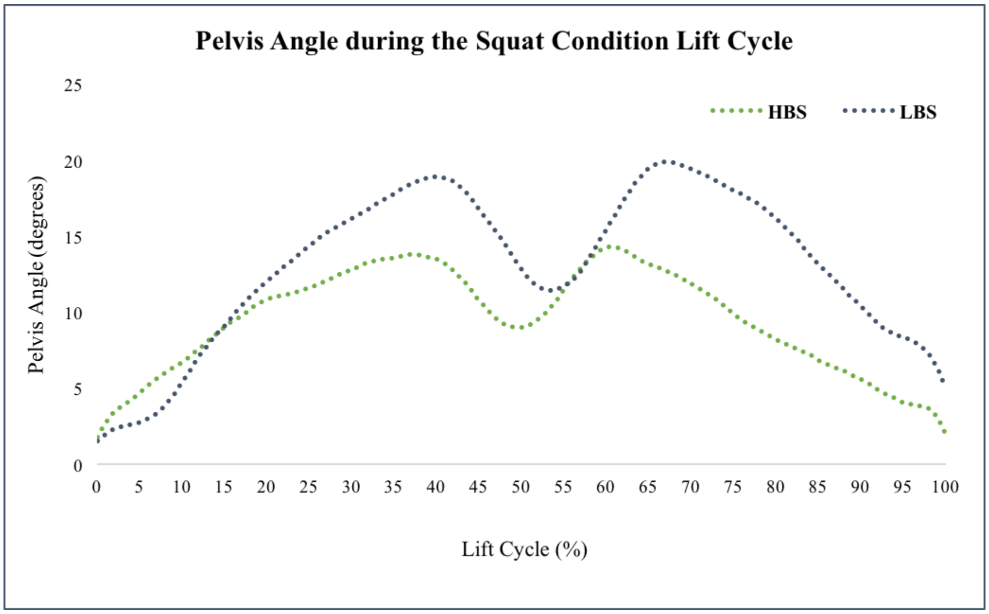

Figure 6.1: Graphs displaying pelvic tilt values during the entire lift cycle for all lifting conditions. A pelvic tilt angle of 0 represent a pelvic position in which a vector connecting the ASIS and PSIS markers is completely parallel with the horizontal ground plane. Increases in pelvic tilt angle indicate a downward shift of the ASIS relative to the PSIS.

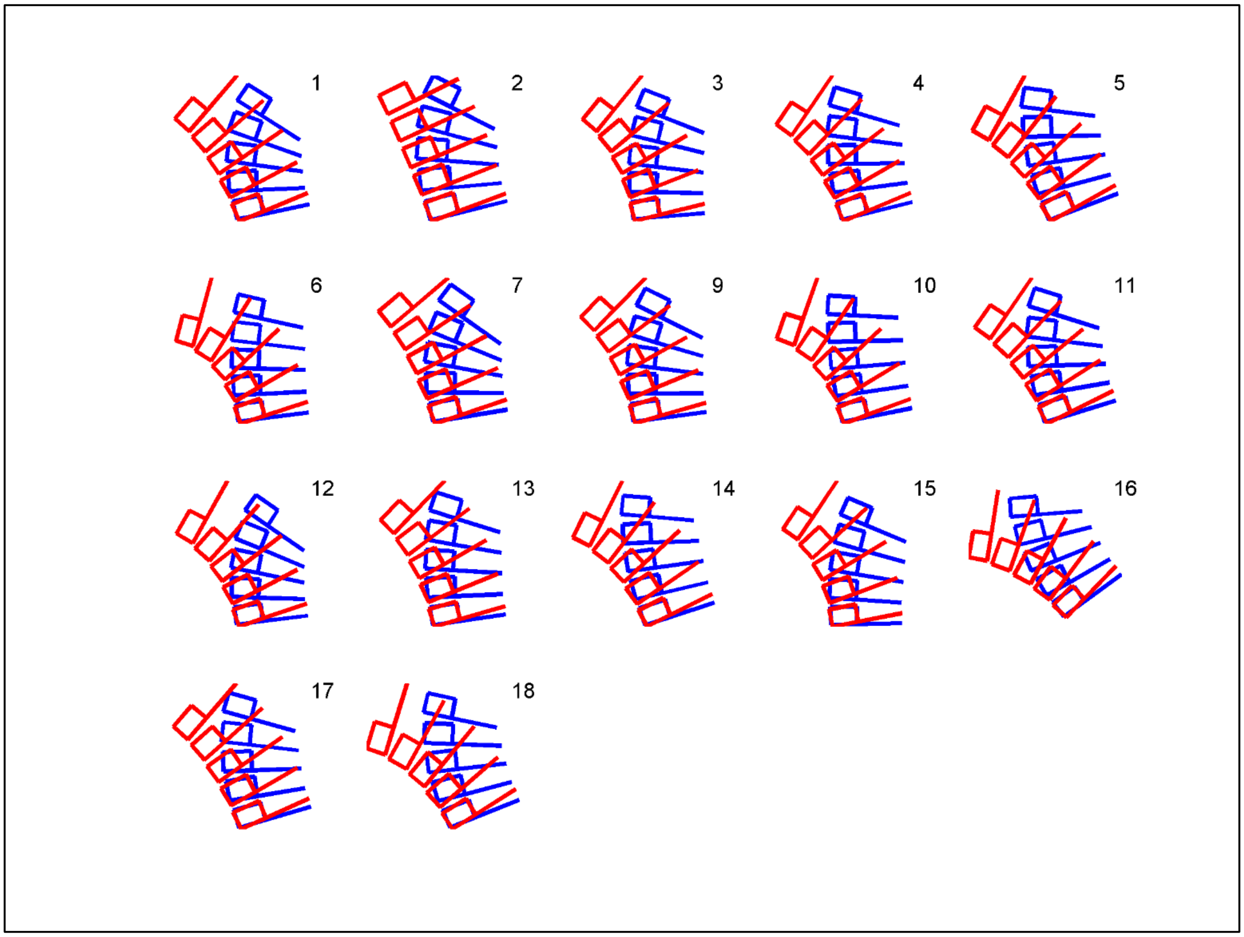

Figure 6.2: Lumbar spine model results for all participants during quiet standing and voluntary trunk flexion. The blue images represent the lumbar spine model positions during quiet standing (neutral). The red images represent the lumbar spine model at maximal voluntary flexion during the forward trunk flexion task. The difference between the two images represents the total change in flexion ROM for each participant estimated by the planar lumbar spine model.