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Relative Intensity of Muscular Effort during Multi-Joint Movement

by

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DEDICATIONS

For my Family, you’ve inspired me to become the person I am today and I will never forget the values you’ve taught me and where I come from.

ABSTRACT

The purpose of this study was to evaluate muscular effort during the squat, a popular resistance training exercise for the triceps surae, quadriceps, hamstrings, and gluteus maximus. Ten females completed deep barbell squats, descending beyond a parallel thigh position, of increasing loads. Relative intensities were calculated for the hip and knee extensors and ankle plantar flexors. Significant *depth* effects were found for the hip and knee extensors, and *load* effects for all muscle groups ($p < .001$). Relative intensities increased with load, where lower squat depths elicited higher knee extensor effort levels. A limitation of inverse dynamics analyses to account for co-contraction was also evaluated. Higher quadriceps intensity levels were revealed at each load once hamstring co-contraction was added to the models. Findings suggest an important role of knee extensor strength in squatting performance and have applications in muscle performance testing in strength and conditioning, as well as rehabilitation settings.

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Lastly, thank you to my family; Mom, Dad and Matthew, whose support, patience and most importantly, love, has and will continue to guide me through life. I would not be where I am today without you.

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CHAPTER 1:

REVIEW OF LITERATURE

INTRODUCTION

Human movement involves tasks requiring multi-joint control. Multi-joint movements are influenced by several muscle groups, each of which may have different functions (Robertson et al., 2008). Their specific functions are indicated by inherent architectural differences such as muscle shape, fibre orientation, fibre type and their attachment locations on bones, which will affect force production and ranges of motion. Consequently, the loading of each muscle is different, due to differences in internal (i.e. anatomic) and external (i.e. external forces) moment arms (Nigg and Herzog, 1999). Current evidence has revealed that the net joint moments (NJM) acting at each joint are not proportionately distributed during a multi-joint task. For example, during squatting exercise, the hip and knee extensor NJM are greater than the ankle plantar-flexor NJM. Recent research by Bieryla et al. (2009) has further suggested that the contribution of a muscle group relative to its maximal force generating ability differs between muscles in the same task. This research demonstrates how differences in internal and external architecture of muscle, in conjunction with segment position changes during a movement, may depict the role of an individual muscle group during multi-joint movement and the relative intensity that the muscle is activated.

ANATOMICAL CONSIDERATIONS

The muscles of the human body can differ by internal characteristics including: 1) proportion of muscle fibre types, and 2) orientation of muscle fibres with respect to tendons. Human studies have indicated that fibre type proportions are highly variable between muscles and muscle groups. The soleus, for example, has a predominately slow twitch muscle fibre composition (approximately 70%) (Edgerton et al., 1975). With respect to inherent differences in muscle fibre and motor unit physiology, it is evident that such muscles are important in slow, low force coordinative movements and for stabilization against external perturbations (Salmons, 2009). The gastrocnemius on the other hand has a greater proportion of fast twitch muscle fibres (approximately 50%), despite both muscles being grouped together as ankle plantar flexor muscles (Edgerton et al., 1975). Other mixed muscle such as the vastus intermedius consists of approximately 47% slow twitch fibres. This mixed proportion design is hypothesized to be functional for both greater force production and higher shortening velocities (Salmons, 2009).

Muscles are also classified based on fibre orientation. Parallel muscles have their fascicles arranged parallel to the long axis of the muscle; therefore the shortening distance of the entire muscle during contraction is the same as for any single fibre, and tension developed will be dependent on the total number of myofibrils and fibre type proportions (Martini et al., 2009; Nigg and Herzog, 1999). The gluteus maximus is an example of a parallel muscle. Convergent muscles have fibres that begin at a broad attachment and merge together at their other attachment. This design increases versatility of the muscle, where the direction of pull can be changed by activating a region at a time, or acting all at once, such as with the pectoralis major (Martini et al., 2009). Consequently, convergent muscles do not pull as hard on the tendon since fibre arrangement causes multi-directional tension (Nigg and Herzog, 1999). With this, it is apparent that the contractile properties of a muscle may also be a function of the index or architecture in addition to fibre type proportions.

Muscles are also classified further by pennation, where one or more tendons run through the body of muscle and fascicles form oblique angles to the tendon. An increased angle of pennation will allow more sarcomeres to fill an available volume as fibres are shorter, thereby increasing their numbers in parallel (Nigg and Herzog, 1999). In contrast, longer fibres have more sarcomeres arranged in series. All sarcomeres may shorten or elongate the same distance and produce the same magnitude of force. Muscles with longer fibres exert forces over a large range of absolute muscle length, whereas short fibred muscles will generate a greater peak force potential due to larger accommodation of fibres in parallel (Nigg and Herzog, 1999). An example of a unipennate muscle of the lower extremity is the vastus lateralis, where fibres are angled to one side of its tendon, as the plumes on a quill pen. The rectus femoris is classified as bipennate, where fibres are angled on both sides of the quadriceps tendon. These are in contrast to a non-pennated muscle such as the semitendinosus, a fusiform muscle, characterized by its spindle-like shape that is wide in the middle and tapers at both ends towards proximal and distal tendons (Martini et al., 2009).

Externally, muscles can be classified by their origin and insertions on limb segments. For example, the gastrocnemius is a biarticular muscle as it crosses two joints: the ankle and knee. Anatomically, its action is described to induce ankle plantar-flexion and knee flexion; however, in a closed kinetic chain exercise such as the squat, the gastrocnemius may play a role in knee extension or ankle dorsiflexion (Bobbert and van Zandwijk, 1994). This muscle feature is important as biarticular muscles may transfer force generated by monoarticular muscles (Voronov, 2004; Bobbert and van Zandwijk, 1994). For example, concentric contraction of the vasti muscles will eccentrically stretch two biarticular muscles, the gastrocnemius and hamstrings at the knee, resulting in a coordinated extension of the ankle, knee, and hip joints. Therefore, the biarticular muscles will simultaneously act on the foot and pelvis in addition to the leg and thigh (Frigo et al., 2010; Voronov, 2004). Furthermore, continued increments in extensor torque produced at the knee by monoarticular vasti muscles may lead to concurrent increased activity of mentioned biarticular antagonistic muscles.

Muscles function by exerting force by acting through tendons, which insert onto bone. The location of the attachment point and the geometrical features of the bone will not only influence the planes motion occurs in, but will complement the architecture of the muscles attached. Bones of the lower extremities involved in squatting movements include the inominate bones, the thigh, tibia and fibula of the leg, and tarsals/metatarsals of the foot. The inominate bones are irregularly shaped bones, consisting of the ishcium, illium, and pubis (Martini et al., 2009). This particular shape of the pelvis is unique as unlike the long bones of the femur and shank, for hip extension, the required length of the gluteus maximus is reduced. In addition, its wider shape allows for greater surface area of attachment, and allows an increased number of sarcomeres in parallel. This is evident as the gluteus maximus has a large cross sectional area (Martini et al., 2009). The femur is the largest and heaviest long bone in the body and its rounded head proximally articulates with the cup shaped acetebulum of the hip to form the hip joint. The hip joint is an example of a ball and socket joint, and permits movement of flexion/extension, adduction/abduction, and internal/ external rotation. The femur then distally articulates with the tibia to form the knee joint. The knee is traditionally classified as a hinge joint, permitting angular movement in a single plane such as flexion/extension of the leg (Martini et al., 2009). However, it is not a true hinge joint as it does permit a limited degree of internal and external rotation (Nigg and Herzog, 1999; Martini et al., 2009). The tibia and fibula of the leg are also long bones, where the tibia and fibula articulate distally with the talus, a tarsal bone of the foot via the ankle joint. The ankle joint is also classified as a hinge joint, permitting plantar/dorsi-flexion ranges of motion. Of the lower extremity, the talocrural joint allows the least motion in the frontal and transverse planes (Martini et al., 2009).

Thus this architecture of the musculoskeletal system defines human movement. Specifically, the architecture of the bones and muscles involved will influence function, including force and torque generating capabilities, and therefore motion. In effect, when a muscle contracts, it will pull on a segment eliciting a movement specific to the muscle’s morphology and the bones it attaches to. Therefore, the biomechanical evaluation of human movement requires that these anatomic features are considered.

BIOMECHANCIAL ANALYSIS OF MULTI-JOINT MOVEMENT

Current models developed to evaluate an individual muscle's force generating ability must attempt to envelope all of its inherent architectural and geometrical mechanical properties. Unfortunately, it is unfeasible to directly measure force generated from an individual muscle; therefore alternative methods have been developed for indirect evaluation of muscular force. Biomechanical techniques for measuring muscle force generation during multi-segment movements involve a combination of kinetic and kinematic analysis. Kinetics is the study of motion in terms of force generation. For human movement, this includes the calculation of joint torques, a rotational effect due to force generated during muscle contraction. Kinematics is the study of the geometry of motion, and these data are often applied using inverse dynamics to calculate net joint moments (NJM). A moment is the rotational effect of a force applied at a perpendicular distance to the axis of rotation (Nigg and Herzog, 1999). Therefore, the NJMs reflect the contribution of all muscle groups acting upon a single joint. The NJM not only indicates the net effect of all muscles acting on a joint, but also the effect of one segment acting on the adjoining segment. From Newton's third law, if muscle action is moving a segment in the clockwise direction, it will be attempting to move the adjoining segment in the counter clockwise directions. For some tasks, the moments of one segment are so large that they will be the dominating effect on the adjoining segment (Nigg and Herzog, 1999), producing movement opposite to that which might be expected from an anatomical perspective.

Inverse dynamic analyses are applied to multi-joint movements to calculate NJMs, using multiple rigid-body link-segment models (Nigg and Herzog, 1999). A major limitation in understanding multi-joint human movement is that typically, only the absolute NJMs are determined. This is an estimate of the active muscular effort. However, this ignores the maximum force generating potential of a muscle group. The NJM relative to the muscle group's maximum torque generating ability has generally not been considered in biomechanical studies. This relative intensity of muscular activation is important in determining relative muscle efforts during a multi-joint task because it illustrates the extent to which a muscle is working in regards to its maximum force generating ability. Experimentally, determining the relative intensity involves relating NJM of muscles during a task with respect to the moment generated by the muscle group during maximal voluntary contractions. Another limitation of absolute NJM is that values represent the total sum of all muscle forces acting upon a joint centre. Due to redundancy of the human musculoskeletal system, there are more muscles than required to cause a particular joint motion, and in combination with simultaneously opposing antagonistic forces, it is difficult to resolve joint moments into individual muscle forces.

SQUATTING MECHANICS

The barbell squat is a complex, load-bearing multi-articular exercise. It is a basic lower body exercise prescribed in training programs for sports and rehabilitation to develop the strength of the quadriceps (rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius), hamstring (semimembranosus, semitendinosus and biceps femoris), triceps surae (gastrocnemius and soleus) and gluteal muscles (gluteus maximus, gluteus medius, and gluteus minumus) (Fry et al., 2003). The movement consists of two phases, the descent and ascent. The descent phase involves simultaneous hip flexion, knee flexion, and ankle dorsiflexion, causing eccentric loading of the quadriceps, triceps surae, and gluteus maximus. Once the desired descending depth has been reached, transition from flexion to extension of the hip and knee and ankle dorsiflexion during the subsequent ascending phase of the squat will result in concentric loading of the quadriceps, gluteus maximus, and triceps surae muscles. In effect, their respective resistive torques will vary in accordance to changes in limb geometry and external resistance applied, in order to return to the initial standing position. Prime movers during the ascent phase are monoarticular gluteus maximus and vasti muscles, and to a lesser extent the solues (Robertson et al., 2008). In turn, the roles of biarticular muscles are hypothesized to function mainly as joint stabilizers and to transfer energy among segments (Robertson et al., 2008; Rao et al., 2009; Escamilla et al., 2001). Previous research has indicated potential eccentric loading of the hamstrings during the ascent phase, however it is predicted that as biarticular hip extensors and knee flexors, there would be no net change in length during the ascending phase and would therefore be considered as being "isometrically" contracted. Similar findings are reported for the gastrocnemius muscle, as from an anatomical perspective, they would induce knee flexion and ankle plantar flexion (McCaw and Melrose, 1999; Escamille, 2001). In addition, according to Wretenberg et al. (1993), peak joint moments occur at the deepest flexion positions of the squat; therefore the depth of the squat may induce higher knee extensor activity as it causes greater vertical ground reaction force.

In order for balance to be maintained in squatting, it is believed that the centre of gravity of the system (body weight plus load of bar) must remain directly over the feet (Flanagan and Salem, 2005). The foot is the most distal segment in the lower extremity providing a small base of support for balance. With this, minor biomechanical alterations in this support surface will most likely influence segment movement strategies in order to optimise centre of gravity position. The combined centre of mass of the barbell and squatter must remain aligned directly above the ground reaction force vector to prevent the individual from tipping forward/backward. To maintain static equilibrium, i.e. to prevent the system from rotating, muscle efforts are required. Given that muscles have a finite force generating ability, this places limitations on the precise motion of segments once additional external loads are imposed such as with a barbell.

Differences in squatting techniques have been shown to affect the kinematic properties of the exercise. In order to maintain the centre of gravity directly over the feet, the leg must be allowed to rotate anteriorly from a vertical position. Fry et al. (2003) measured changes in the distribution of forces between the knees and hips during two squat protocols; 1) the knees were permitted to move anteriorly past the toes (unrestricted) or 2) a wooden barrier prevented the knees from moving anteriorly past the toes (restricted). Knee torque measurements were greater during the unrestricted squat (150.1 ± 50.8 N•m unrestricted vs. 117.3 ± 34.2 N•m for restricted) while hip torque was excessively increased during restricted squatting (28.2 ± 65.0 N•m unrestricted vs. 302.7 ± 71.2 N•m for restricted). Restricted squats also produced more anterior lean of the trunk, leading to forces being inappropriately transferred to the hips and low-back region. With this, in order to maintain balance during the squat, ankle dorsi-flexion must be allowed so the knees can move forward to prevent excessive trunk lean and tipping forward.

Alternative squatting techniques have been adopted by strength athletes, as seen with powerlifting, in order to take advantage of maximal force generating abilities of the strong hip extensor musculature by widening squatting stance. McCaw and Melrose (1999) showed no significant changes in quadriceps activity as foot position was widened; however increased hip extensor activity of the gluteus maximus and hamstring were noted. Squatting with a wider stance involves increasing the amount of external rotation of the femur during descent, yet maintaining the same degree of knee flexion. Therefore, in order to maintain the centre of gravity of the system over the feet, less anterior movement of the knees is required, resulting in increased forward torso lean and demands of the hip extensor musculature.

Flanagan and Salem (2005) measured NJM of the hip extensors, knee extensors, and ankle plantar-flexors during the squat with increasing loads. The NJMs were analysed in relation to the others involved. As load increased, they observed increases in NJMs in the hip extensors, whereas the knee extensor NJM did not change. These findings can be attributed to changes in centre of pressure (COP); since the barbell was located anteriorly to the participant's centre of mass during the squats, increased load shifted the resistive forces and concomitantly COP forward. Forward deviation of COP will in turn increase the moments at the hip. Chiu et al. (2006) also noted similar changes in the COP during flywheel resisted squats due to the anteriorly directed pull of the flywheel cable. Together, these studies indicate that as COP moves anteriorly, the moment arm of the hip extensors is increased, while that of the knee extensors is decreased and this results in an increase in the contribution of the hip extensors relative to the knee extensors.

Hay et al. (1983) examined the assumption that each muscle group increases force generation in parallel to increasing load during squatting using dynamic rigid-link theoretical modeling; however this was only found to be true when kinematics of the squat were held constant (i.e. constant technique, velocity of movement, and load). As later reported by Flanagan and Salem (2005) and Chiu et al. (2006), as load increases and centre of pressure is altered, such constant technique may be unattainable as resistive load increases. Changes in technique would be expected to result in compensatory mechanisms such as distributing required joint demands onto other muscles groups, due to primary mover weakness and inability to provide joint equilibrium with more desirable squatting techniques (Van der Heijden et al., 2009). A study by Salem and Salinas (2003) compared bilateral kinetics and kinematics during squatting in individuals after anterior cruciate ligament reconstruction. They noted that in the unaffected limb, knee extensor moments were greater; however in the affected limb, hip extensor moments were greater. Recent evidence by Palmieri-Smith et al. (2008) has found quadriceps weakness in the affected limb of individuals with anterior cruciate ligament injury. Taken together, this demonstrates how knee extensor weakness is addressed by the motor system by increasing the contribution of additional muscle groups to compensate.

A consequence of compensation strategies is that they may create undesirable kinematics. As mentioned, a common muscle strategy due to knee extensor weakness may be a shifting of demand on to the hip extensor musculature (Yoshioka et al., 2007). Yoshioka et al. (2007) evaluated peak joint moments during a sit-to-stand task and determined that hip and knee values were complementary. When joint moment requirements were shifted to the hip, this manifested kinematically with a forward torso lean and reduced forward leg inclination. Increased forward torso lean is an unfavourable movement stratgegy, which may lead to acute injuries such as muscle strains, and/or chronic injuries such as spastic, stretching of muscles. Cappozzo et al. (1985) noted increased spinal compressive loads between joints at L3-L4 vertebrae in accordance to increased forward torso lean during squat motions. Therefore, reduced knee extensor moments and increased hip extensor moments due to excessive forward torso lean may result in both acute and/or chronic lower back injuries. This forward torso lean would reduce the required amount of anterior knee movement during the squat and kinematically manifest as decreased leg inclination. This improper squatting technique may be a manifestation of general knee extensors weakness as they may be working at higher effort levels in comparison to the hip extensors.

RELATIVE INTENSITY OF MUSCLE EFFORT

Consideration of a muscle group's maximum force generating potential would allow determination of the relative intensity of muscular effort, which could be compared across active muscle groups. Relative intensity of muscle action can be measured as the ratio of the NJM of a particular muscle group in a multi-joint task to its NJM during a maximal voluntary contraction (Bieryla et al. 2009). This methodology would allow observation of how various muscle groups combine synergistically to produce coordinated multi-joint movement, as each muscle acts at a different relative intensity. Furthermore, muscle weakness would only be expected to affect movement if the relative intensity approaches maximum. Thus, this analysis would allow determination of the muscle group weakness and how this would affect multi-joint movement tasks.

Anderson et al. (2007) developed a model for determining maximal NJM generating ability taking into account length-tension relations during dynamic tasks. Length-tension properties of active muscles describe the relationship between maximal force production of a muscle fibre (or sarcomere) and its length

(Nigg and Herzog, 1999). Muscle lengthening or shortening during activity will dictate that amount of overlap between thick and thin myofilaments, and in turn determine the number of possible cross-bridge formations and total force generated. Wrentenberg et al. (1996) noted differences in moment arm lengths of knee muscles with respect to knee flexion angle during *in vivo* MRI imaging analyses. With this, it is evident that models for determining muscular strength must be angle- and gender-specific. This may be accomplished by determining maximum muscular strength at various joint positions, specific to those observed during a multi-joint task (Anderson et al., 2007), allowing NJM generated during multi-joint movement to be related to maximum NJM at the same joint angle.

Bieryla et al. (2009) applied this model to demonstrate, during a sit-to-stand task, disproportionate relative intensities of the hip extensors, knee extensors, and ankle plantar-flexors. In elderly participants, the knee extensors contributed more to task performance, requiring ~80% of their maximum ability, followed by the hip extensors at ~25% and the ankle plantar-flexors at ~25%. Sit-to-standing movements do not include external loads in addition to the individual’s body weight as required in strengthening exercises such as the squat. The knee extensors would then be hypothesized to be unable to further contribute during loaded squatting, as they would have already been highly active without additional load and therefore potentially limit the elderly individual’s lifting ability. The hip extensors would then be expected to increase their contribution at higher loads and result in changes in the geometry of the movement to maintain equilibrium. This evidence illustrates the importance of first understanding how muscles function during multi-joint tasks before studying the interaction of intra- and inter- muscle coordination, such as fatigue during multi-joint tasks.

SUMMARY

In summary, multi-joint movements involve simultaneous contraction of several muscles of differing torque generating abilities, which are in turn based on anatomical inherent and external characteristics of the musculoskeletal system. However the distribution of force generation is not uniform between joints and the extent to which each muscle group is active with respect to its maximum force generating abilities is unknown. Thus, in order to understand multi-joint coordination, relative intensity of muscle actions must first be determined. Furthermore, it will contribute to understanding muscle compensation strategies that may occur as load is increased and primary movers are unable to sustain or contribute force generation due to weakness and how these mechanisms manifest in technique changes (such as indicated by segment kinematics). This thesis is intended to investigate the kinetics of a multi-joint squat task in order to determine the relative intensity of muscle activation, as well as address current issues in biomechanical analysis of joint kinetics through anatomical and geometrical consideration of simultaneously active agonist and antagonistic muscles during the weighted barbell squat.

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CHAPTER 2:

Relative Intensity of Muscular Effort of the Lower Extremities with Respect to Squat Depth and Barbell Load.

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INTRODUCTION

The barbell squat is a complex, load-bearing multi-articular exercise. It is a basic lower body exercise prescribed in training programs for sports performance and rehabilitation to develop the quadriceps (rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius), hamstring (semimembranosus, semitendinosus and biceps femoris long head), triceps surae (gastrocnemius and soleus) and gluteus maximus muscles (Fry et al., 2003). It is often assumed that all muscles are working at the same relative intensity. It is well known that the mechanical effort, biomechanically calculated as net joint moment (NJM), at each joint in a multi-joint task varies between joints. Flanagan and Salem (2005) measured NJM of the hip extensors, knee extensors, and ankle plantar-flexors during the squat with increasing loads. The NJM of each muscle group was analysed in relation to the others involved. As load increased, they observed increases in mechanical effort in the hip extensors, whereas the knee extensor did not change. However these findings did not take into account *relative* mechanical effort, that is, to what extent each muscle group is working with respect to its maximum force generating abilities.

Consideration of a muscle group's maximum voluntary force generating ability would allow determination of the relative intensity of muscular effort, which would allow the mechanical effort to be compared across muscle groups. Relative intensity of muscle mechanical effort can be measured as the ratio of the NJM of a particular muscle group in a multi-joint task to its NJM during a maximal voluntary contraction (MVC) (Bieryla et al., 2009). These authors applied this methodology to observe that the contribution of the hip and knee extensors and ankle plantar-flexors in elderly participants relative to their maximal force generating ability differs between muscle groups during a sit-to-stand task. The muscle group having the highest relative intensity was the knee extensors (80%), whereas the hip extensors and ankle plantar-flexors had a low relative intensity (28% and 26% respectively). The sit-to-stand task involves a squatting motion. However, squats used for resistance training differ in the variety of barbell loads and squatting depths that are possible. In addition, elderly populations have significally reduced maximal voluntary force generating abilities (Yoshioka et al., 2007). Thus, it is important to understand how barbell load and squat depth influence the relative intensity of muscle mechanical effort during squatting in an athletic population who regularly participates in heavy resistance training regimes.

Waters et al. (1974) observed that hip extensors generated their largest moment at 90 degrees hip flexion, and lower moments at 45 and 0 degrees of hip flexion. These variations in strength are attributed to the well-known muscle length-tension relation and variations in muscle moment arms at different joint angles (Anderson et al., 2007). Therefore, to determine a muscle group's relative intensity, it is imperative to compare the active NJM (i.e. from the squat) to the maximum NJM taking into account the joint angles where the moments are generated. The purpose of this study was to investigate relative intensity of the hip extensors, knee extensors, and ankle plantar flexors considering the influence of squat depth and barbell load. This study builds on methodology developed by

Anderson et al. (2007) and Bieryla et al. (2009) to account for length-tension and joint angle-moment arm relation.

Based on prior research by Bieryla et al. (2009), who found the knee extensors were active at near-maximal relative intensities in the sit-to-stand, an unloaded variation of the squat exercise, it was hypothesized that during heavy squatting exercise the knee extensors would be active at a high relative intensity at low barbell loads, leading to increased contribution of the hip extensors and ankle plantar flexors to compensate with increasing barbell load. We also hypothesized that based on Wretenberg et al. (1993), who found large increases in NJM at full squat depths, relative intensity would increase with squat depth, particularly in squatting below a parallel position.

MATERIALS AND METHODS

Participants. Ten women with a minimum of 1 year's experience performing the back squat were recruited to participate in this investigation. Inclusion criteria required that each participant be able to squat a minimum barbell load of 1.0 times their body weight (Table 2-1). Exclusion criteria for participants included previous lower extremity or lower back orthopaedic and musculoskeletal injuries that would have prevented the exercises from being performed safely. This sample size allows detection of within subject effect size differences of 0.2 standard deviation (small difference) while minimizing type I error to 5% and type II error to 20% (Power = 80%). Participants completed 3 sessions spaced approximately 1 week apart. Study procedures were explained to participants and they provided written informed consent, as approved by the University of Alberta Faculties of Physical Education and Recreation, Agricultural, Life and Environmental Sciences and Native Studies Research Ethics Board. During the course of the investigation, participants were instructed to refrain from any strenuous lower extremity activities outside the laboratory sessions.

Table 2-1. Subject Characteristics.

	Height (cm)	Bodyweight (kg)	Age (years)	Year's Experience	1 RM (kg)	1RM/ Bodyweight
Subject Means (SD) (n=10)	166.9 (7.5)	62.4 (6.5)	23 (2)	4.3 (3.1)	80.5 (10.1)	1.3 (0.2)

Procedures. In the first session, participants were tested for their one repetition maximum (1 RM) in the high-bar back squat exercise (Figure 2-1). A minimum of parallel thigh depth was required, where the top of the thigh at the inguinal fold was at the same height or below the top of the patella. The procedure of Kraemer and Fry (1995) was used for 1 RM testing, where load was incrementally increased until participants reached a barbell load where failure (i.e. inability to lift the weight) occurred. The second session involved recording of high-bar back squat performance using 3D motion analysis to determine NJM. The third session involved maximum strength testing of the hip extensors, knee extensors, and ankle plantar-flexors using single-joint isometric dynamometry.

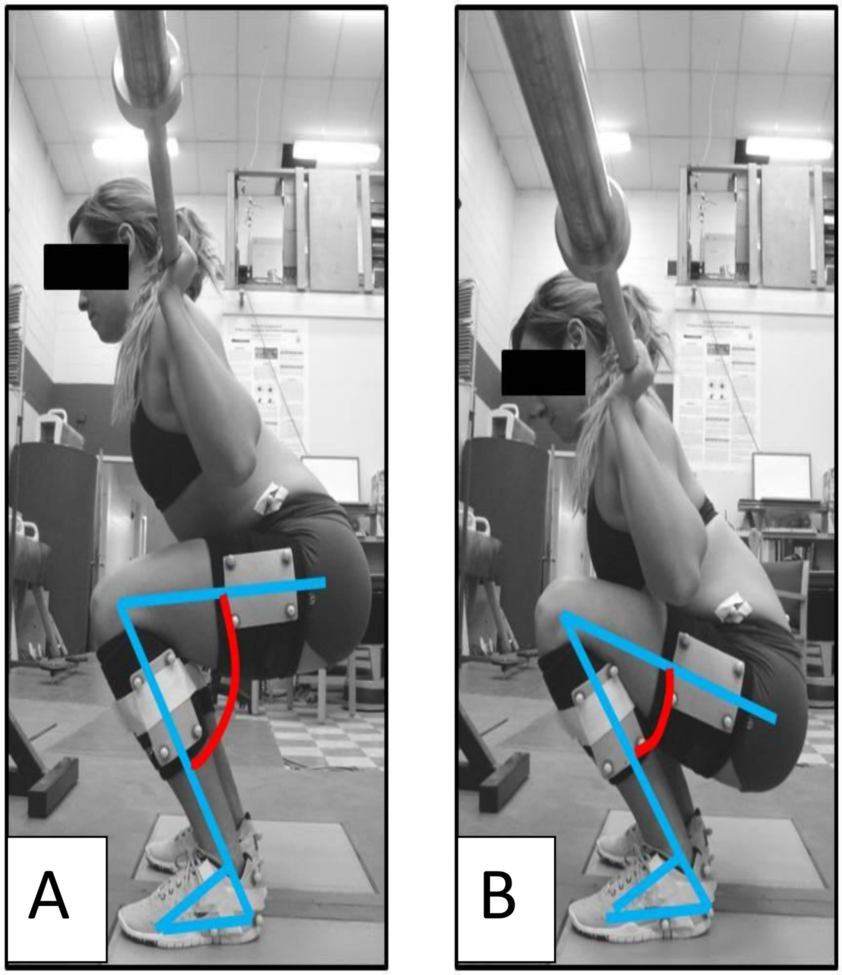

Figure 2-1. A) Parallel and B) deep squat depths

Motion Analysis. The second session involved participants performing high-bar back squats at barbell loads of 50%, 60%, 70%, 80%, and 90% of 1 RM. Participants performed 3 repetitions at each load. Adequate rest times, approximately 3-5 minutes, were allowed between each set to prevent potential fatigue or postactivation potentiation effects (Chiu et al., 2004). Also, participants were asked to perform the eccentric phase squat in a controlled manner in order to control angular velocity and prevent stretch reflex influences (Manabe et al., 2007). Participants were asked to use their normal squat technique and speed of ascent was not standardized. All trials were performed in a motion analysis laboratory with 9 optoelectronic cameras (Pro-Reflex MCU240; Qualisys, Sweden) collecting data at 120Hz. Simultaneous ground reaction forces were collected at 1560HZ with two force platforms (AMTI OR6-6; AMTI, Watertown, MA). During the squats, participants were asked to place one foot on each force platform. For motion analysis, a six degree-of-freedom retro-reflective marker set was worn by participants (Chiu and Salem, 2006). This marker set included calibration and tracking markers placed on the participant's trunk, thigh, leg, and foot (Figure 2-2). Calibration markers were placed on the medial and lateral femoral epicondyles, medial and lateral malleoli of the ankle, and greater trochanters of the left and right legs to define knee, ankle, and hip joint centres respectively. Tracking markers were placed on L5/S1 and left and right iliac crests to track the pelvis. Cluster tracking markers, consisting of three or four markers fixed on a semi-rigid thermoplastic plate, were placed on the thigh, leg, and foot of both limbs. Calibration markers were only used during static and dynamic trials to define segments. All markers were placed by the same investigator who had previously demonstrated high test-retest reliability in placing of these markers in the months immediately prior to the investigation.

All data were processed and analyzed in Visual 3D software (C-Motion, Germantown, MD) using standard 3D inverse dynamic procedures. Data were digitally filtered using a 4th order recursive low-pass Butterworth with a 6 Hz cut-off frequency. Segment kinematics were generated from the retro-reflective markers, identifying the proximal and distal ends of segments. Ground reaction forces were applied at the feet, and segment reaction forces and moments were carried up to the shank and thigh to calculate NJM at the ankle, knee, and hip. The primary variables of interest were NJM and joint angles at the hip, knee, and ankle during the concentric phase of the squat.

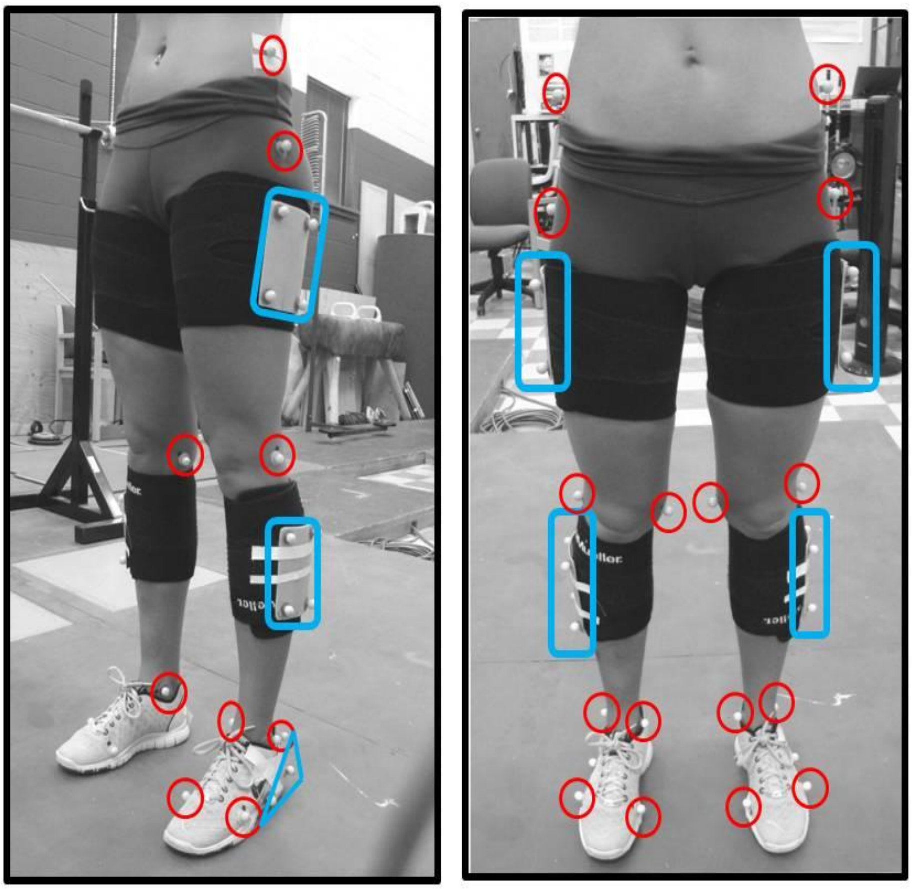

Figure 2-2. Hybrid marker set placement. Red indicates calibration markers. Blue indicates cluster tracking markers

Isometric Strength Testing. The final session involved assessing maximum voluntary net joint moments of isometric exercises for the hip extensors, knee extensors, and ankle plantar flexors. Maximum voluntary NJMs of the hip extensors, knee extensors, and ankle plantar flexors were measured isometrically to represent maximum muscle force generating ability. The procedures for determining maximum voluntary NJM were modified from Anderson et al. (2007) to take into account length-tension relations and joint angle changes in muscle moment arms. Maximum NJM was measured at 30, 60, and 90 degrees at the hip and knee (0 degrees equals full extension), and 5, 15, and 25 degrees at the ankle (0 degrees equals neutral and positive angles are dorsiflexion).

A custom-built dynamometer (Figure 2-3) was used for maximum strength assessment. The design of the dynamometer was based on the leg extension apparatus described in Schilling et al. (2005). Briefly, to measure force applied, a tension-calibrated load cell (MLP-350, Transducer Techniques, Temecula, CA) was placed in line with the cable secured to the floor. The force applied to the load cell was calibrated by hanging known masses and measuring the resulting voltage response. NJMs were calculated as the cross product of the length of the machine lever arm and the force measured by the load cell. The analog signal from the load cell was channelled through a signal conditioner (TMO-1-2200, Transducer Techniques), digitally converted using a 16-bit analog-to-digital board (USB-1616FS, Measurement Computing, Norton, MA), and recorded to a personal computer. Data were sampled at 500Hz using APAS software (Ariel Dynamics; Temecula, CA). Participants were instructed to contract as hard as possible for a 4 second action. Loud verbal encouragement was provided. Two trials were performed at each angle. Sufficient rest was provided between trials to minimize fatigue. For each joint and angle, only the trial with the highest maximum voluntary NJM was analyzed to ensure that values were not an underestimation due to unfamiliarity with the device. Data were digitally filtered using a 4th order recursive Butterworth with a 10 Hz cut-off frequency.

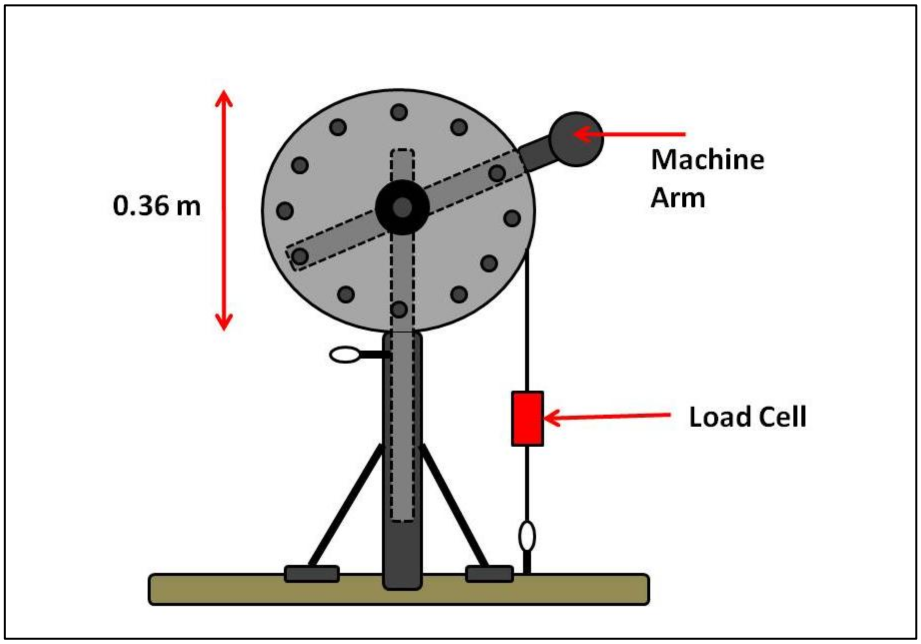

Figure 2-3. Custom built dynamometer designed for evalution of maximum voluntary strength of hip and knee extensors and ankle plantar-flexors

Data Analysis. Relative intensity of muscle mechanical effort was determined as the ratio of NJM during the squat to the maximum voluntary isometric NJM from strength testing. Polynomial regression equations were fit for each participant's maximum voluntary isometric NJM curves. For task NJM values, squat depth was operationally defined based on knee joint angle and squat depths of 30, 60, 90, and 105 degrees were analyzed. The NJM of the hip, knee, and ankle were determined at each of these points in the concentric phase of the squat. The corresponding hip and ankle angles at these four squat depths were also determined (i.e. with respect to knee flexion angles) in order to relate their respective angles back to subject specific regression equations to determine the maximum isometric NJM for each muscle group at the four squat depths. All relative intensities were expressed as a percentage (i.e. percentage of the maximum isometric NJM).

Statistical Analyses. To assess the effects of barbell load (50%, 60%, 70%, 80%, and 90% 1 RM) and squat depth (knee angles 30, 60, 90, and 105 degrees) on relative intensity, a 4 x 5 (load by depth) multivariate ANOVA was used. Multivariate levels consisted of relative intensity data at the hip, knee, and ankle joints. Where multivariate ANOVA were significant, univariate ANOVA were used to determine at which multivariate level significant differences occurred. Where appropriate, Tukey HSD was used for subsequent post-hoc comparisons of load and depth. Alpha was set *a priori* at $\alpha=0.05$. A univariate ANOVA was also used to test effects of load on leg angulation during the squat, where a reduction in leg angle at each knee position would suggest a forward torso lean as load was increased. Lastly, univariate tests of load effects on COP forward deviation during the squat were also used to note any changes in kinematics. In addition to significance testing, the magnitude of potential differences was assessed using Cohen's d effect size statistic.

RESULTS

The 4 x 5 multivariate analysis omnibus test found two main effects: a squat depth main effect ($p < .001$) and a barbell load main effect ($p<.001$). No depth by load interaction was found ($p=0.122$). Univariate ANOVA for the depth main effect indicated significant effects for the hip and knee ($p<.001$) but not for the ankle ($p=0.361$). The effects of depth on relative intensity at the ankle, hip, and knee are presented in Figure 2-4. The relative intensity of the knee extensors demonstrated a plateau between approximately 60 and 90 degrees of knee flexion and was then followed by an increased in slope intensity past 105 degrees. In contrast, the hip extensor relative intensity peaked at approximately 105 degrees of knee flexion and subsequently declined with further depth. The effect of barbell load on relative intensities demonstrate a linear proportional trend in the ankle and hip, however a plateauing in knee extensor relative intensity occurred beyond 70% 1RM (Figure 2-5).

Statistical analysis also revealed no significant changes in squatting kinematics with respect to depth and load ($p>.05$). There was no significant reduction in leg inclination or changes in COP shifting during the squat, suggesting that there was no apparent hip extensor shifting strategy as load was increased indicative of a forward torso lean.

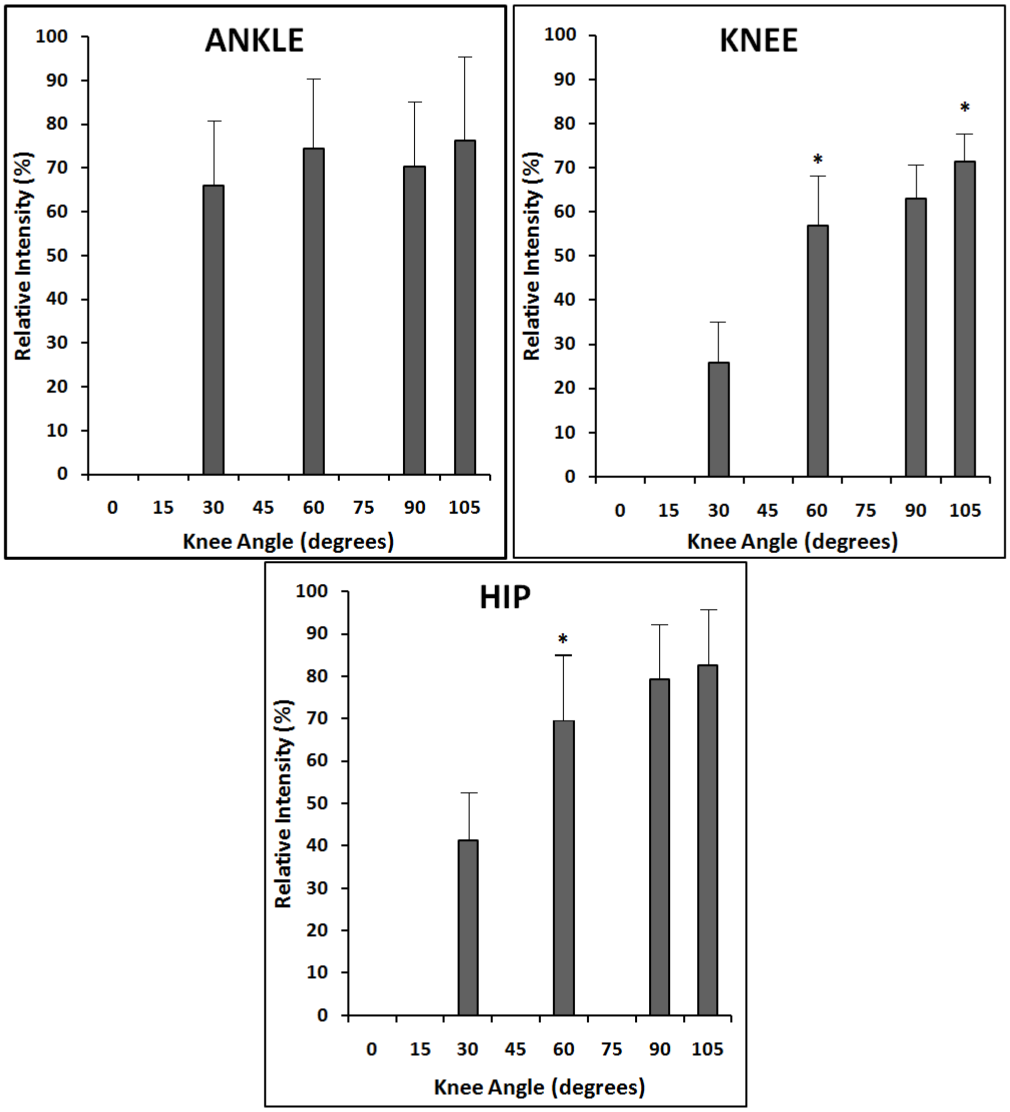

Figure 2-4. Relative intensities of the ankle plantar-flexors, knee extensors and hip extensors with respect to squat depth. Error bars represent standard deviations. * indicate significant difference between previous depth position.

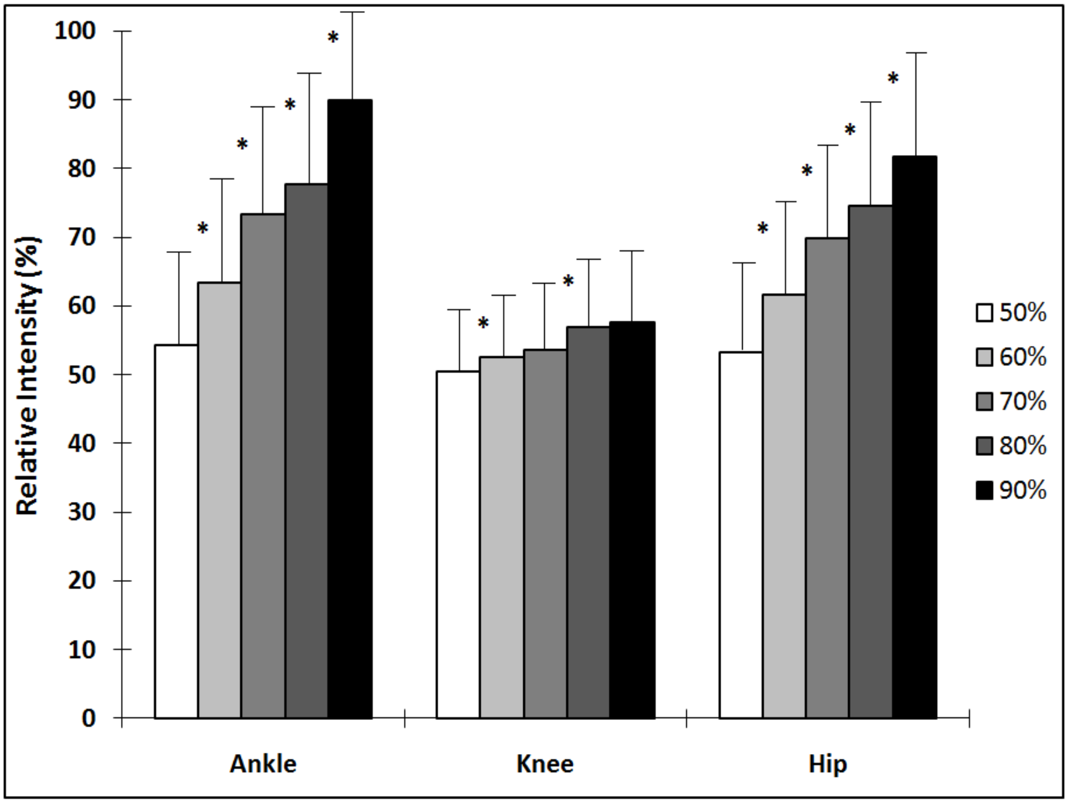

Figure 2-5. Relative intensities of the ankle plantar-flexors, knee extensors, and hip extensors with respect to barbell load (%1RM). Error bars represent standard deviation. * indicates significant difference from previous loads.

DISCUSSION

This study identified two significant factors that influence the relative intensity of muscle mechanical effort profiles of the hip extensors, knee extensors, and ankle plantar-flexors associated with the barbell squat in females. The first influential factor on relative intensity of muscle mechanical effort of the hip and knee was squat depth. The finding that no statistically significant depth effect was present for ankle plantar-flexor relative intensity is not surprising due to mechanics affecting ankle plantar-flexor NJM calculation. Ankle NJM is calculated from forces acting on the foot. The largest influence on calculation of ankle NJM is the centre of pressure location relative to the foot (Nigg and Herzog, 1999). Our data suggest that no apparent centre of pressure location change occurs with increasing depth. In contrast, large ranges of motion achieved by the shank and thigh segments would be expected to cause increased NJM for the hip and knee extensors with increasing squat depths.

The hip extensor relative intensity data indicated the effect of depth on relative intensity, where plateauing occurred at approximately 80-90 degrees of hip flexion then subsequently decreasing at further hip flexion angles. This can be explained from a mechanical perspective as a parallel thigh position with respect to the floor at approximately 90 degrees is where the maximum moment arm of the hip extensors is achieved (MA 90), which then decreases as depths progress beyond parallel positions (Figure 2-6).

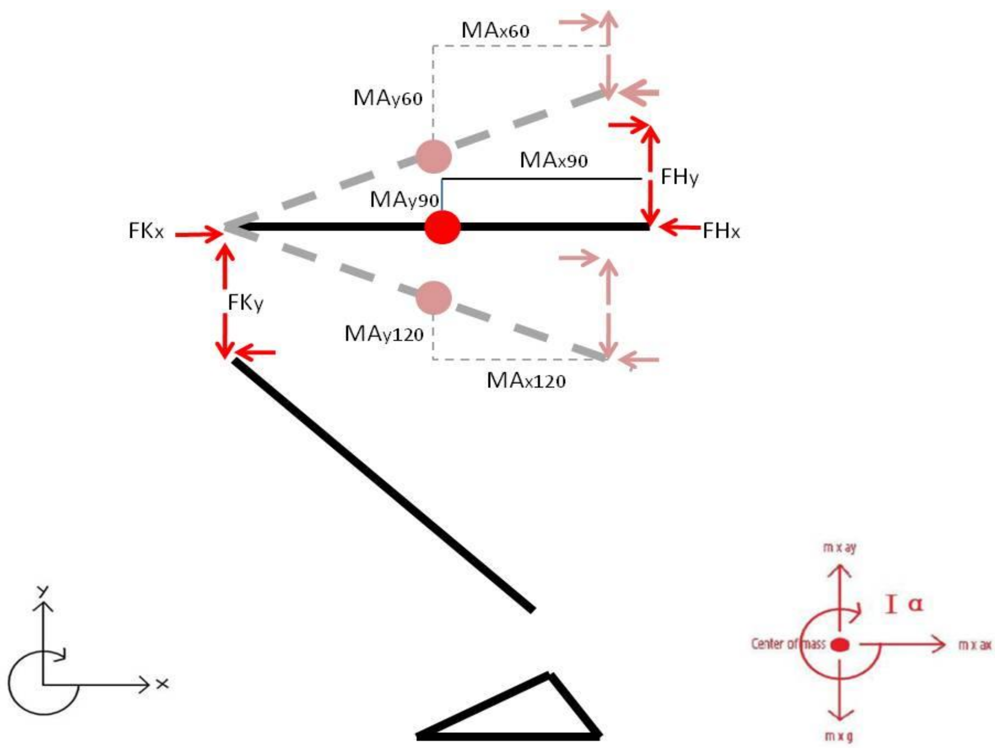

Figure 2-6. Hip extensor moment arm changes with respect to changes in thigh angle: 60, 90 and 120 subscripts refer to thigh angles. MA: moment arm. FH: hip joint reaction forces. FK: knee joint reaction forces.

Alternatively, the effect of depth on relative intensity of the knee extensors indicated a plateauing in relative intensity between 60 and 90 degrees of knee flexion, followed by a sudden increase in slope beyond 105 degrees. In contrast to the thigh segments, during the squat the leg angle does not approach 90 degrees due to anatomical limitations in the possible dorsiflexion range of motion at the ankle. From Figure 2-1, it appears that forward leg inclination increases during the initiation of the squat and later as the individual squats below parallel.

Escamilla (2001) concluded that no superior knee extensor activity would be achieved by descending below a parallel thigh position; however their protocols only required participants to descend to a parallel depth. It is possible to squat well-below a parallel depth, thus extrapolating the findings of Escamilla (2001) to full squat depths is not warranted. Our findings indicate that the parallel depth used by Escamilla (2001) did not represent the true contributions of the knee extensors during a full squat; therefore their interpretation of results may be misleading. Our findings would suggest that performing deep squats would require greater knee extensor efforts. To corroborate, Salem and Powers (2001) found a similar plateau in knee extensor NJM at a moderate knee flexion range, and a trend for increased NJM at 110 degrees. Taken together, Salem and Powers (2001) and our data suggest that if an individual is capable of squatting beyond 105 to 110 degrees, knee extensor NJM and relative intensity will increase considerably. An investigation by Wretenberg et al. (1996) also saw that NJM values increased dramatically when squatting below a parallel depth. Figure 2-7 shows relative intensity data of the knee extensors for the participant who achieved the greatest knee flexion angle (approximately 135 degrees), demonstrating increased knee extensor effort intensity beyond 105 degrees of flexion.

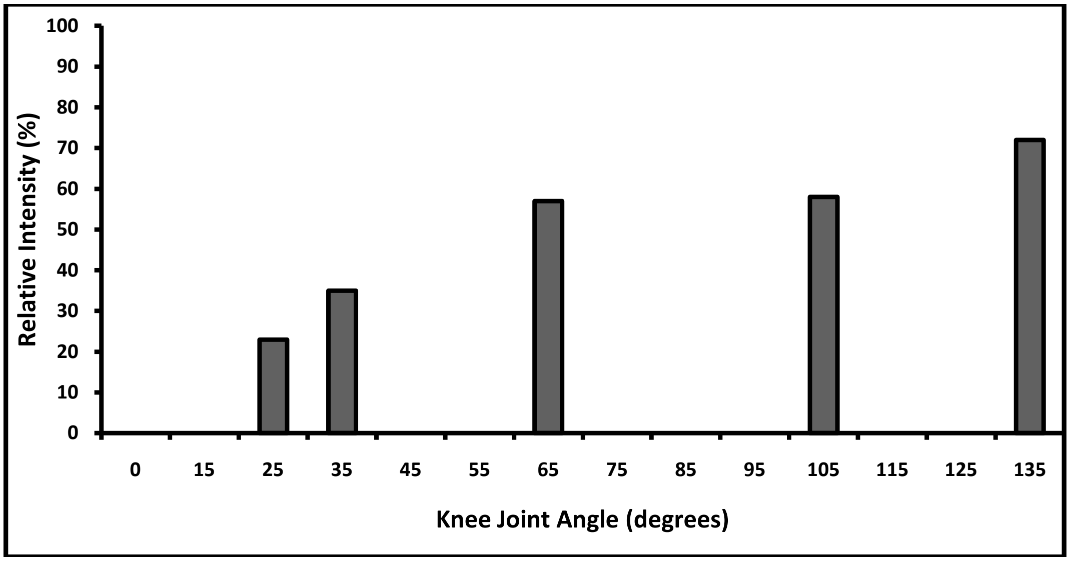

Figure 2-7. Knee extensor relative intensity at 50% 1RM for subject who achieved the lowest squat depths.

The relative intensity of hip extensor, knee extensor, and ankle plantar-flexor mechanical efforts were also found to be affected by the amount of external loading applied during the squat. The current literature indicates that the barbell squat in resistance training programs strengthens the quadriceps, hamstring, triceps surae, and gluteal muscle groups (Robertson et al., 2008; Fry et al., 2003; Flanagan and Salem, 2008; Salem and Powers, 2001; Palmeri-Smith et al., 2008). This investigation demonstrated the required effort imposed on these muscles was influenced by the amount of external resistance applied. Ankle plantar-flexor and hip extensor relative intensity was observed to increase in parallel with increased barbell load. In contrast, the knee extensor relative intensity increased only while barbell load increased from 50% to 70% 1 RM and remained relatively constant at higher barbell loads. The most plausible rationale for why knee extensor relative intensity did not increase would be kinematic changes, specifically forward leg inclination and location of centre of pressure. However there was no reduction in forward shank inclination ($p<.0001$), which would reduce the moment arms of the vertical forces acting on the shank, and centre of pressure relative to foot placement remained constant as barbell load increased. Therefore these findings cannot be explained by simple mechanical differences.

An alternate explanation for the lack of increase in knee extensor relative intensity with increasing barbell load may be the major limitation of NJM determination via traditional inverse dynamic techniques. Specifically, the NJM represents the minimum torque required to satisfy the equations of motion; they do not account for antagonistic muscle co-contraction. The knee extensor NJM presents the sum total of all muscle torques acting upon the knee joint, which includes the quadriceps and the antagonistic hamstrings and gastrocnemius. Waters et al. (1974) noted that 40-50% of hip extensor moments is generated by the hamstrings. The hamstring muscle group consists of biarticular muscles that would contribute an extensor moment at the hip and a flexor moment at the knee. Since hip extensor relative intensity was increased with barbell load, the contribution of the hamstrings to hip extensor moment must also increase. Subsequently, a large knee flexor moment would also be expected. Because of this antagonistic co-contraction, the hamstring activity impairs our ability to resolve a true picture of quadriceps moment generation. Thus the knee extensor NJM represents the minimum agonist quadriceps moment; however, the actual activation of these muscles could be much greater. Similar consequences would also be expected to occur at the knee as a function of the gastrocnemius as its biarticularity contributes to an ankle plantar-flexor torque and knee flexor torque. Therefore, the analysis of knee extensors in this investigation is likely to have underestimated the relative intensity of muscle mechanical effort.

In summary, this investigation presents for the first time the influence of squat depth and barbell load on relative intensity of muscle mechanical effort. The findings of this study are pertinent in understanding the role of the squat exercise for strength training and rehabilitation. The understanding of optimal squat technique for eliciting training adaptations is critical to properly design training programs. This study suggests that barbell squats should be performed to the greatest depth that an individual is anatomically able to achieve, as this allows increased loading of the knee extensors for any given load. It is particularly important to consider that performing squats to a parallel depth alone will not sufficiently load the knee extensors, as the knee extensor relative intensity plateaus at this depth. Further analysis is required to elucidate the true effect of barbell load on quadriceps moment and relative intensity, as antagonist co-contraction likely has a large effect on knee extensor NJM during heavy squatting.

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CHAPTER 3:

Estimation of Quadriceps Relative Intensity by the Application of Hamstring Co-Contraction Modeling.

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INTRODUCTION

The consideration of how hard a muscle group is working relative to its maximum force generating potential allows researchers to compare coordinative activation strategies during complex multi-joint tasks across active muscle groups. This knowledge is pertinent for examination of how technique changes manifest as compensation strategies due to muscle weakness, fatigue, and/or inability to activate muscles, for example due to injury (Salem and Salinas, 2003). Of particular interest in strength and conditioning is the ability to accurately evaluate the performance of individual muscle groups, in particular the quadriceps femoris (rectus femoris, vastus lateralis, vastus intermedius, vastus medialis), which are fundamental extensors and stabilizers of the knee joint. In rehabilitative settings, restoration of the quadriceps muscle mass and performance is of primary importance following anterior cruciate ligament injury. Salem and Salinas (2003) compared bilateral kinetics and kinematics during squatting in individuals after anterior cruciate ligament reconstruction. They noted that in the unaffected limb, knee extensor moments were greater; however in the affected limb, hip extensor moments were greater. Recent evidence by Palmieri-Smith et al. (2008) has found quadriceps weakness in the affected limb of individuals with anterior cruciate ligament injury. Yoshioka et al. (2007) additionally noted that a minimum torque of 1.53 $N \bullet m \bullet kg^{-1}$ summed between the knee and hip joint and values at each may be distributed by several strategies. Together, this demonstrates how knee extensor weakness is addressed by the motor system using muscle compensation strategies, resulting in increased contribution of mechanical effort by other muscle groups in an attempt to perform the task.

Our previous investigation (Chapter 2) found that relative intensity of the knee extensors did not increase with increasing barbell load. Our analysis of kinematic effects, specifically shank angle and center of pressure, do not explain this finding; therefore our results could not be resolved to a simple mechanical effect caused by movement pattern changes. A limitation in the calculation of net joint moment (NJM) using inverse dynamics procedures is the issue of co-contraction; the NJM represents the contribution of all muscle groups acting upon a single joint, and therefore does not resolve the knee extensor joint moments into individual muscular forces or moments of the quadriceps. In turn, biarticular muscles are hypothesized to function mainly as joint stabilizers and to transfer energy among segments (Robertson et al., 2008; Rao et al., 2009; Escamilla, 2001). Previous research has indicated an important paradoxical role of the hamstrings during the ascent phase, where being biarticular in nature, its increased co-contraction activity as an agonist hip extensor would be expected to oppose quadriceps by generating a knee flexor moment (Hortobagyi et al., 2003; Fujita et al., 2011). Therefore, the knee extensor NJM in our previous investigation may not have accurately represented the relative intensity of the quadriceps during squatting with heavy loads.

It is not experimentally viable to measure muscle force *in vivo*. A useful technique commonly used to estimate the extent of muscle activation and force is the amplitude of the EMG signal. Under isometric conditions, the relationship between muscular force is frequently linear with EMG amplitude, where incremental changes in muscular force produce linearly related changes in EMG amplitude. This is due to a combination of motor unit recruitment and increases in motor unit firing rate. McCaw and Melrose (1999) reported that during squatting, hamstring EMG amplitude increased in proportion to increasing barbell load. Additionally, Fujita et al. (2011) noted an un-proportional increase in EMG amplitude and NJM values of the knee extensors between young and elderly participants during a sit-to-stand task. This was attributed to elderly individuals' knee extensor weakness, in which they rely heavily on co-contraction of the hamstring during such tasks, as reported by Hortobagyi et al. (2003).

Our previous work (Chapter 2) further found that the hip extensors were active at high relative intensities, particularly as barbell load increased. Waters et al. (1974), using sciatic nerve block, reported that the hamstrings contributed 40-50% to maximum hip extensor moment, depending on hip joint angle. Taken together, these investigations allow us to model the magnitude of hamstring co-contraction and therefore estimate the true knee extensor relative intensity during heavy squatting. The feature of heavy squatting that allows this modelling to be performed is the high relative intensity of the hip extensors. In theory, if the hip extensors are performing maximally at 100% relative intensity, the independent contributions of the gluteus maximus and the hamstrings can be estimated using the data of Waters et al. (1974). If the hip extensor relative intensity was below 50% of maximum, such estimations could not be made. As we report relative intensities greater than 50% and reaching 100% of maximum, we can estimate the independent contribution of the hamstrings using one of three assumptions.

The co-contraction of the hamstrings during hip extension may be accomplished by three possible strategies: 1) an equal proportion of gluteus maximus and hamstrings at all activation levels, 2) initial gluteus maximus recruitment at lower intensities, followed by increased synergistic activation of the hamstring as intensity is increased, and 3) initial hamstring recruitment at lower intensities, followed by additional recruitment of gluteus maximus at greater intensities. Strategy 1 assumes that load sharing among the hip extensor muscles is equal, in other words, the mechanical effort required is divided evenly among all contributing muscles. Using the data from Waters et al. (1974), the independent contributions of the two muscle groups can be estimated simply as a function of joint angle.

Strategy 2 has been referred to as fitting the law of parsimony, where the simplest solution is employed. At lower intensities, mono-articular muscles are recruited initially, followed by addition of biarticular groups in order to meet moment generating demands imposed upon the joint (Basmajian and Latif, 1957). Based on investigations of parsimony of muscle strategies and research by Waters et al. (1974), the gluteus maximus would be responsible for hip extensor moments up to 50-60% of maximum, where further moments are generated by the hamstrings. The hamstring contribution can therefore be determined as the residual contribution by subtracting the estimated maximum gluteus maximus contribution from the true relative intensity during squatting. As the opposite, hamstrings are activated preferentially over gluteus maximus, Strategy 3 will not be considered in modelling. The second strategy in turn, based on investigations of Waters et al. (1974) would imply that at all loads, the hamstring would be responsible for 40-50% of hip extensor torque values.

We argue that knee extensor NJM and relative intensity, as we have previously reported (Chapter 2), during the loaded barbell squat does not accurately represent the quadriceps moment; rather it underestimates the true quadriceps moment due to antagonist co-contraction. Thus, the objective of this investigation was to develop two models that more accurately describe the quadriceps moment by estimating co-contraction of the hamstrings at the knee during the concentric phase of the squat. Data presented were taken from the previous chapter that investigated relative intensity levels of the hip extensors, knee extensors, and ankle plantar flexors during the loaded the barbell squat. Based on the recruitment strategies presented, two models were be developed: Model 1 which assumes an equal contribution of the hamstrings and gluteus maximus to hip extensor NJM (Strategy 1) and Model 2 which follows the concept of parsimony (Strategy 2). Model 1 calculates the maximum hamstring co-contraction; whereas Model 2 represents the minimum hamstring co-contraction. With this, we hypothesized that true quadriceps relative intensity during heavy squatting exists between these upper and lower limits of hamstring co-contraction.

METHODS

Participants. Ten women with a minimum of 1 year's experience performing the back squat were recruited to participate in this investigation. Inclusion criteria required that each participant be able to squat a minimum load of 1.0 time their body weight. Exclusion criteria for participants included previous lower extremity or lower back orthopaedic and musculoskeletal injuries that would have prevented the exercises from being performed safely. Participants completed 3 sessions spaced approximately 1 week apart. Study procedures were explained to participants and they provided written informed consent as approved by the University of Alberta Faculties of Physical Education and Recreation, Agricultural, Life and Environmental Sciences and Native Studies Research Ethics Board. During the course of the investigation, participants were instructed to refrain from any strenuous lower extremity activities outside the laboratory sessions.

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	Height (cm)	Bodyweight (kg)	Age (years)	Year's Experience	1 RM (kg)	1RM/ Bodyweight
Subject Means (SD) (n=10)	166.9 (7.5)	62.4 (6.5)	23 (2)	4.3 (3.1)	80.5 (10.1)	1.3 (0.2)

Data Collection Procedures. In the first session, participants were tested for their one repetition maximum (1 RM) in the high-bar back squat exercise (Figure 2-1). A minimum of parallel thigh depth was required, where the top of the thigh at the inguinal fold was at the same height or below the top of the patella. The procedure of Kraemer and Fry (1995) was used for 1 RM testing, where load was incrementally increased until participants reached a barbell load where failure (i.e. inability to lift the weight) occurred. The second session involved recording of high-bar back squat performance using 3D motion analysis to determine NJM. The third session involved maximum strength testing of the hip extensors, knee extensors and ankle plantar-flexors using single-joint isometric dynamometry.

Motion Analysis. The second session involved participants performing high-bar back squats at barbell loads of 50%, 60%, 70%, 80%, and 90% of 1 RM. Participants performed 3 repetitions at each load. Adequate rest times, approximately 3-5 minutes, were allowed between each set to prevent potential fatigue or postactivation potentiation effects (Chiu et al., 2004). Also, participants were asked to perform the eccentric phase squat in a controlled manner in order to control angular velocity and prevent stretch reflex influences (Manabe et al., 2007). Participants were asked to use their normal squat technique and speed of ascent was not standardized. All trials were performed in a motion analysis laboratory with 9 optoelectronic cameras (Pro-Reflex MCU240; Qualisys, Sweden) collecting data at 120Hz. Simultaneous ground reaction forces were collected at 1560HZ with two force platforms (AMTI OR6-6; AMTI, Watertown, MA). During the squats, participants were asked to place one foot on each force platform. For motion analysis, a six degree-of-freedom retro-reflective marker set was worn by participants (Chiu and Salem, 2006). This marker set included calibration and tracking markers placed on the participant’s trunk, thigh, leg, and foot (Figure 2-2). Calibration markers were placed on the medial and lateral femoral epicondyles, medial and lateral malleoli of the ankle, and greater trochanters of the left and right legs to define knee, ankle, and hip joint centres respectively. Tracking markers were placed on L5/S1 and left and right iliac crests to track the pelvis. Cluster tracking markers, consisting of three or four markers fixed on a semi-rigid thermoplastic plate, were placed on the thigh, leg, and foot of both limbs. Calibration markers were only used during static and dynamic trials to define segments. All markers were placed by the same investigator who had previously demonstrated high test-retest reliability in placing of these markers in the months immediately prior to the investigation.

All data were processed and analyzed in Visual 3D software (C-Motion, Germantown, MD) using standard 3D inverse dynamic procedures. Data were digitally filtered using a 4^{th} order recursive low-pass Butterworth with a 6 Hz cut-off frequency. Segment kinematics were generated from the retro-reflective markers, identifying the proximal and distal ends of segments. Ground reaction forces were applied at the feet, and segment reaction forces and moments carried up to the shank and thigh to calculate NJM at the ankle, knee, and hip. The primary variables of interest were NJM and joint angles at the hip, knee and ankle during the concentric phase of the squat.

Isometric Strength Testing. The final session involved assessing maximum voluntary net joint moments of isometric exercises for the hip extensors, knee extensors, and ankle plantar flexors. Maximum voluntary NJMs of the hip extensors, knee extensors, and ankle plantar flexors were measured isometrically to represent maximum muscle force generating ability. The procedures for determining maximum voluntary NJM was modified from Anderson et al. (2007) to take into account length-tension relations and joint angle changes in muscle moment arms. Maximum NJM were measured at 30, 60, and 90 degree joint angles at the hip and knee (0 degrees equals full extension), and 0, 15, and 30 degree joint angles at the ankle (0 degrees equals neutral and positive angles are dorsiflexion).

A custom-built dynamometer (Figure 2-3) was used for maximum strength assessment. The design of the dynamometers was based on the leg extension apparatus described in Schilling et al. (2005). Briefly, to measure force applied, a tension-calibrated load cell (MLP-350, Transducer Techniques, Temecula, CA) was placed in line with the cable secured to the floor. NJMs were calculated as the cross product of the length of the machine lever arm and the force measured by the load cell. The analog signal from the load cell was channelled through a signal conditioner (TMO-1-2200, Transducer Techniques), digitally converted using a 16-bit analog-to-digital board (USB-1616FS, Measurement Computing, Norton, MA) and recorded to a personal computer. Data were sampled at 500Hz using APAS software (Ariel Dynamics; Temecula, CA). Participants were instructed to contract as hard as possible for a 4 second action. Loud verbal encouragement was provided. Two trials were performed at each angle. Sufficient rest was provided between trials to minimize fatigue. For each joint and angle, only the trial with the highest maximum voluntary NJM was analyzed to ensure that values were not an underestimation due to unfamiliarity with the device.

Data were digitally filtered using a 4^{th} order recursive Butterworth with a 10 Hz cut-off frequency.

Data Analysis. Relative intensity of muscle mechanical effort was determined as the ratio of NJM during the squat to the maximum voluntary isometric NJM from strength testing. Polynomial regression equations were fit for each participant's maximum voluntary isometric NJM curves. For task NJM values, squat depth was operationally defined based on knee joint angle, and squat depths of 30, 60, 90 and 105 degrees were analyzed. The NJM of the hip, knee, and ankle were determined at each of these points in the concentric phase of the squat. The corresponding hip and ankle angles at these four squat depths were also determined (i.e. with respect to knee flexion angles) in order to relate their respective angles back to subject specific regression equations to determine the maximum isometric NJM for each muscle group at the four squat depths. All relative intensities were expressed as a percentage (i.e. percentage of the maximum isometric NJM). The difference between the current investigation and our previous report was that the quadriceps moment was estimated from the calculated knee extensor NJM corrected for hamstring co-contraction. Hamstring co-contraction was modelled using two methods.

Model Building. The ability to distribute joint moments into constituent individual forces from muscles would be dictated by the geometrical relation between the muscle's position and the centre of rotation of the joint it crosses. Nemeth and Ohlsen (1985) presented the moment arm of the hamstring muscles acting at the hip joint at 5 degree intervals from 0 to 90 degrees of hip flexion. A second-order polynomial regression was fit to these data for hip angles greater than 90 degrees. From these data, forces of the hamstring muscles were calculated. Wretenberg et al. (1996) used identical methods to Nemeth and Ohlsen (1985) to determine the moment arm of the hamstring muscles acting at the knee joint. Wretenberg et al. (1996), only reported data at 0, 30, and 60 degrees of knee flexion; therefore the regression lines were fit to these data to estimate the moment arms at 5 degree intervals from 0 to 105 degrees of knee flexion. These data were best fit with linear regression equations, and data for the semitendinosus, semimembranosus, and biceps femoris – long head were averaged. From these moment arms, the knee flexor moment generated by the hamstrings was estimated. The quadriceps moment was then calculated by adding the knee extensor moment calculated using inverse dynamics and the knee flexor moment.

To determine the contribution of the hamstrings to the total hip extensor NJM, two models were employed. In Model 1, it was assumed that the hamstrings contributed an equal percentage of the total hip extensor NJM regardless of the relative intensity of the hip extensors. Data were taken from Waters et al. (1974). These data followed no obvious trend in relation to hip joint angle, however, the spread of data was fairly small; therefore a linear regression was fit to the data. The percentage contribution of the hamstrings to the total hip extensor moment was multiplied by the hip extensor NJM to estimate the moment generated by the hamstrings.

In Model 2, the concept of parsimony was applied. In this model, it was assumed that the hamstrings would not be active until the gluteus maximus reached its maximum torque generating ability. For this model, the gluteus maximus contribution to maximum moment generation was determined using the data from Waters et al. (1974). This was the inverse of the hamstring contribution described above. The hamstring contribution was then calculated as the residual of the hip extensor relative intensity minus the percentage of maximum moment the gluteus maximus could contribute. For example, if the hip extensor relative intensity (as determined in Chapter 2) was 90%, and the gluteus maximus at the same hip angle could contribute 52% of maximum hip extensor moment, the hamstring contribution would be 38% (90% - 52% = 38%). The hamstring percentage was then multiplied by the hip extensor moment to determine the hamstring moment at the hip.

RESULTS

Representative figures for estimated quadriceps relative intensity levels using Methods 1 and 2 are shown in Figures 3-1 through 3-4 for each squat depth (as represented by knee joint angle) evaluated. Figures also include knee extensor relative intensity data from the previous chapter as a means of comparing the net effect of accounting for hamstring co-contraction at the knee during the loaded barbell squat. For each joint angle, relative intensity for Models 1 and 2 were on average greater once hamstring co-contraction was taken into account. Quadriceps relative intensities for Model 1 were generally greater than for Model 2.

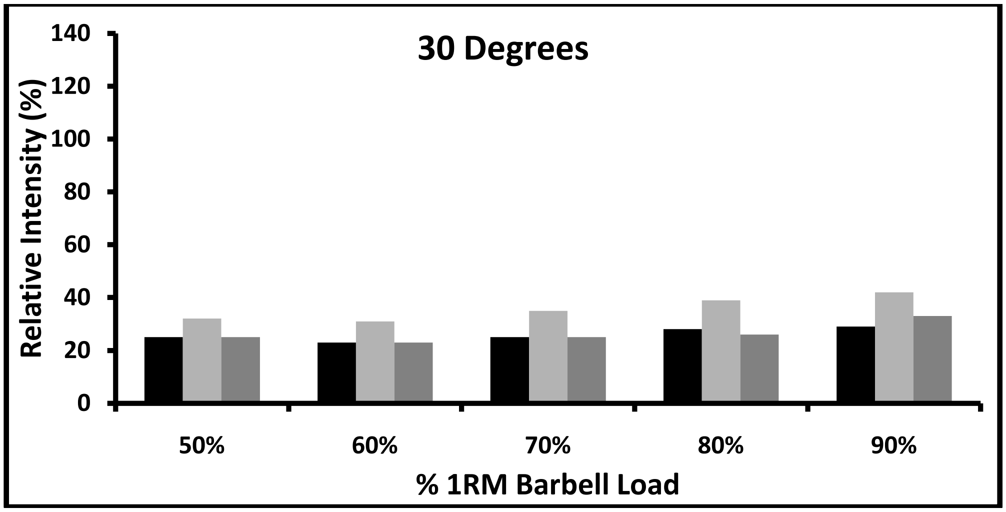

Figure 3-1. Model comparison of knee extensor relative intensities with respect to barbell load at 30 degrees of knee flexion. Black – knee extensor NJM; Light gray – Quadriceps moment (Model 1); Dark gray – Quadriceps moment (Model 2).

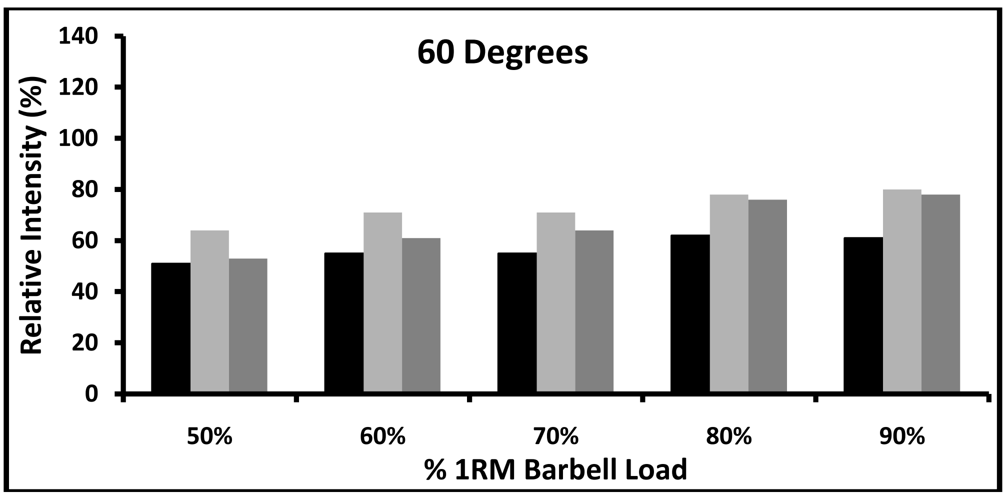

Figure 3-2. Model comparison of knee extensor relative intensities with respect to barbell load at 60 degrees of knee flexion. Black – knee extensor NJM; Light gray – Quadriceps moment (Model 1); Dark gray – Quadriceps moment (Model 2).

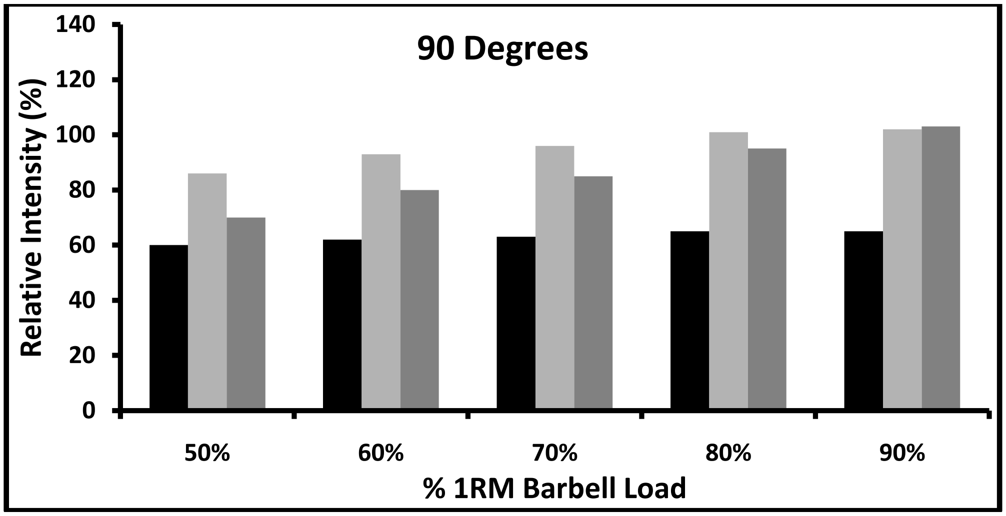

Figure 3-3. Model comparison of knee extensor relative intensities with respect to barbell load at 90 degrees of knee flexion. Black – knee extensor NJM; Light gray – Quadriceps moment (Model 1); Dark gray – Quadriceps moment (Model 2).

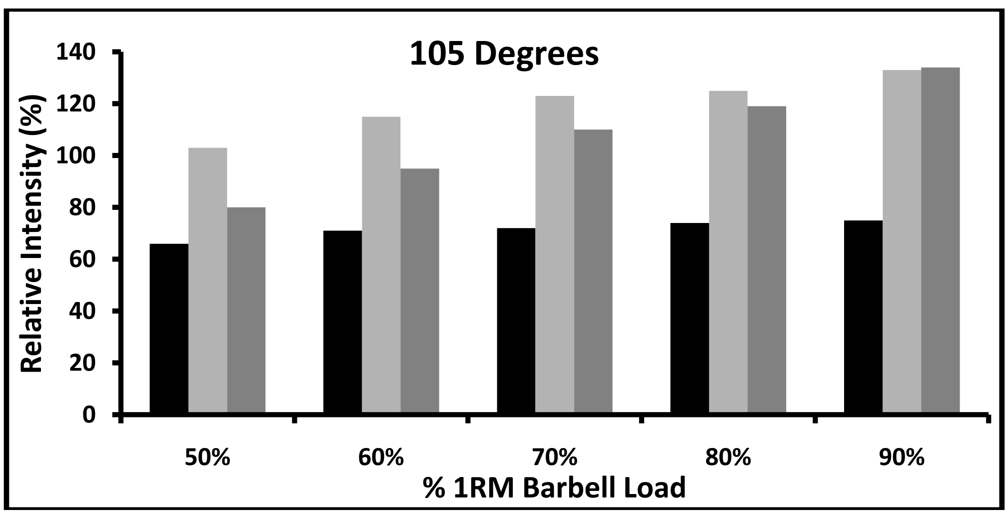

Figure 3-4. Model comparison of knee extensor relative intensities with respect to barbell load at 105 degrees of knee flexion. Black – knee extensor NJM; Light gray – Quadriceps moment (Model 1); Dark gray – Quadriceps moment (Model 2).

DISCUSSION

The findings of the investigation strongly suggest that the influence of co-contraction was a major factor impacting the interpretation of knee extensor NJM and relative intensity using traditional inverse dynamics techniques. The muscles crossing the knee are a unique example of how biarticularity may influence the net moments acting on a joint. The recruitment of the hamstring muscles in hip extension causes antagonistic co-contraction at the knee, therefore the *knee extensor NJM* underestimates the *quadriceps moment*. In this investigation, we took advantage of the heavy loaded squat data and relative joint kinetic calculations from the previous investigation. In combination with research collections on hamstring anatomy (Nemeth and Ohlsen, 1985; Wretenberg et al., 1996) and recruitment strategy (Waters et al. 1974).

Model 2 was developed based on parsimony, suggesting that the gluteus maximus would be solely responsible for hip extensor moments up to 50 to 60% of maximum hip extensor moment, as it is the primary mono-articular muscle involved in hip extension. Reports by Basmajian and Latif (1957) have found mono-articular muscles are recruited at low forces, whereas biarticular muscles contribute only at higher forces. This is the fundamental application of parsimony to human movement, where the simplest solution is applied. The use of biarticular muscles prior to mono-articular muscles would require synergist muscles to neutralize unwanted motion at other joints, which would increase the complexity of the task. When the monoarticular muscles are not sufficient to meet the moment demands, the additional moment would be generated by biarticular muscles – in the case of the hip extensors, the hamstrings. In effect, corrections to quadriceps relative intensity using Model 2 would represent the minimum antagonistic effect of the hamstrings at the knee.

In contrast, Model 1 would represent the highest potential co-contraction effect of the hamstrings. In this model, hamstrings and gluteus maximus contribution was uniform for all hip extensor moments generated. Based on the data analyzed, correction of knee extensor NJM to quadriceps moment using Model 1 resulted in higher quadriceps relative intensity at all barbell loads. The relative intensities at all barbell loads at 105 degrees of knee flexion exceeded 100% (Figure 3-4), meaning the quadriceps moment was greater than the measured maximum moment generated during isometric strength testing. As the assumptions in both models are likely unrealistic, the true quadriceps moment and relative intensity is likely less than Model 1 estimates and greater than Model 2 estimates.

A confounding factor that is not accounted for in our investigation is the effect of thigh-calf contact. Zelle et al. (2007) reported that thigh-calf contact is present during squatting tasks. Their investigation indicated that at deep knee flexion angles, thigh-calf contact forces were up to 34.2% body weight. The effect of thigh-calf contact is a passive (i.e. soft tissue) knee extensor moment, which would reduce the demands on the quadriceps. In our investigation, quadriceps relative intensity only exceeded 100% at 105 degrees of knee flexion using Model 1. Taken together, Model 1 estimates may be correct, but misunderstood as the passive knee extensor would account for the moment greater than that generated by the quadriceps muscles. Therefore, the presence of tissue contact with deep squatting imposes a limitation on accurate quadriceps effort estimates.

Fujita et al. (2011) investigated the relationship between EMG activity of the torque values of the knee extensors during a non-loaded squat in young and elderly populations. They noted a pronounced age-related loss in leg extensor force generating abilities which was associated with knee extensor activity levels during the body weight squat. A breakpoint knee extensor strength of 1.9 Nm/kg was found to be a threshold for which knee extensor EMG % intensity and NJM % intensity values became disproportionate. They attributed this to possible presence of hamstring co-contraction if a weaker individual was working at a greater effort level. This co-activity of the hamstrings would depreciate knee extensor NJM values and not EMG amplitude if present. Research by Hortibagyi et al. (2003) has also indicated that the elderly population perform activities of daily living (ADLs) near their maximal force generating abilities and rely heavily on co-activity of the biceps femoris; as ADL relative effort of the knee extensors was increased, hamstring co-contraction was significantly increased as well. Therefore if the knee extensors are highly active at lower loads during the barbell squat, further increments in barbell load will result in greater hamstring co-activity.

Our data suggest that even at low loads, the quadriceps is active in generating large moments. These moments increase in a linear fashion similar to the ankle plantar flexors and hip extensors as we have previously reported (see Figure 2-5; Chapter 2). Therefore, it can be theorized that the quadriceps contribute substantially to squat performance. In effect, traditional inverse dynamics techniques are incapable of representing the true quadriceps moment generation at the knee during loaded multi-joint movements such as the squat. Instead, antagonistic activity depreciates knee extensor NJM values.

The models in this analysis did not account for gastrocnemius co-contraction, which would have similar effects to the hamstrings – the ankle plantar-flexor relative intensity is comparable to hip extensor relative intensity. Future research should consider the antagonist effect of the gastrocnemius to knee extensor moment. However, this argument would only strengthen our contention that the knee extensor NJM underestimates the true quadriceps moment.

In summary, the use of traditional inverse dynamics calculations of NJMs is inadequate in the examination of relative intensities of muscle groups in heavily loaded multi-joint movement, as they are unable to account for co-contraction of biarticular muscles such as the hamstrings and gastrocnemius which have antagonistic activity at the knee. The results of this investigation have implications in clinical settings of which the accurate evaluation of muscle performance is crucial to the success in rehabilitative program design and implementation.

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CHAPTER 4:

SUMMARY, CONCLUSION, AND PRACTICAL APPLICATIONS

SUMMARY

The main findings of this investigation demonstrated a positive relationship between both barbell load and squat depth, with muscle mechanical efforts during the ascent phase of the squat. Greater squat depths were achievable with greater leg forward leg angulation, which in turn elicited greatest knee extensor activity, highly desirable stimuli in strength and conditioning as well as rehabilitative settings. Also, findings of the investigations imply that as barbell load is increased in a linear incremental fashion, effort levels of the ankle plantar-flexors, knee extensors, and hip extensors are also increased in a linear fashion in accordance to external resistance. However, the appearance of a knee extensor plateau at greater loading intensities could not be explained by simple mechanical solutions (such as movement technique changes).

The limitation of traditional inverse dynamic analysis is that NJM calculations do not account for co-contraction of antagonistic muscle groups, in particular the hamstrings. Previous research has indicated an important role of biarticular muscle contribution during multi-joint movement where as load is increased in the squat, increased contribution of the hamstrings for hip extension results in an increased opposing knee flexor moment at the knee. This realization lead to the primary objective of Chapter 3: *Estimation of Quadriceps Relative*

Intensity by the Application of Hamstring Co-Contraction Modeling. By compiling data on hamstring moment arms with respect to the hip and knee (Nemeth and Ohlsen, 1985; Wretenberg et al., 1996), two separate modeling strategies were developed to resolve quadriceps effort activity; one taking into account the law of parsimony (Basmajian and Latif, 1957) (Model 2) and the other the investigation of hamstring contributions in hip extension by Waters et al. (1974) (Model 1). Models 1 and 2 represented the upper and lower potential levels of quadriceps relative intensities with respect to load.

RESEARCH CONCLUSIONS

This is the first work to investigate the NJMs of the hip extensors, knee extensors, and ankle plantar flexors, taking into account their maximum voluntary joint moments during a high intensity, multi-joint strength training task: the squat. Previous studies have solely considered absolute net joint moments and muscle contributions, neglecting the evidence that each muscle group may be working at different intensities relative to its maximal levels at a given load. In doing so, we have found four major conclusions:

1) A directly positive relationship exists between muscle effort contributions and external resistance applied during multi-joint movement; however relative intensities are not evenly distributed across muscle groups involved.
2) Superior knee extensor activity is elicited at greater squat depth, in particular below a parallel squat position.

3) The quadriceps knee extensor contribution is responsible for high contributions of collective lower-extremity effort during loaded barbell squats, where initially high relative intensity levels at 50% 1RM loading suggest that their strength is the limiting factor in squat performance.
4) The use of traditional inverse dynamics calculations of NJMs is inadequate in the examination of relative intensities of muscle groups in multi-joint movement. They are unable to account for co-contraction of biarticular muscles such as the hamstrings and gastrocnemius which have antagonistic activity to the quadriceps during the concentric phase of the squat.

PRACTICAL APPLICATIONS

This research will ultimately contribute to understanding the underlying mechanisms as to how mechanical stimuli translate to adaptation through understanding the extent to which muscle/muscle groups are active to cause specific strengthening results. The methodologies of this study will allow us to examine how technique changes manifest as compensation strategies due to muscle weakness, fatigue, tightness and/or inability to activate muscle in a coordinated fashion. This has applications in rehabilitation for injury, including prevention and treatment, as a restoration factor to educate individuals about how to properly perform a specific exercise, as well as to address what mechanical corrections are required. In that, this research is expected to be beneficial for strength and conditioning professionals by increasing our understanding of how muscles coordinate multi-joint movements via relative muscle contribution analysis. Changes with respect to intensity and technique may be pertinent for prescribing effective training programs (exercise selection, volumes, and intensities). Furthermore, the research has elucidated how tasks should be properly performed when aiming to target specific muscle group strength training, as well as in the prevention of chronic overuse injuries due to improper technique.

The experimental methodology employed is important to the study of multi-joint movement, in particular identifying how different muscles contribute to task performance. This research bridges the disciplines of anatomy, biomechanics, and physiology to provide insight into the control of human movement. The methodologies presented for relative intensity data analysis, as well as co-contraction modeling, can be applied to study exercises in strength and conditioning and rehabilitation, as well as to the evaluation of and instruction of movement skills such as in sport and activities of daily living. Further understanding of how different muscles contribute to task performance is necessary to develop training regimens to improve, restore, or optimize human movement.

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APPENDIX A:

INSTITUTIONAL REVIEW BOARD DOCUMENTATION

Notification of Ethics Approval

Study ID:	Pro00016957
Study Title:	Relative Intensity of Muscular Effort during Multi-Joint Movement
Study Investigator:	Megan Bryanton
Funding/Sponsor:	National Strength and Conditioning Association (NSCA)
Approval Expiry Date:	November 22, 2011

I have received your application for research ethics review and conclude that your proposed research, including revisions received October 13 and November 23, 2010, meet the University of Alberta standards for research involving human participants (GFC Policy Section 66). On behalf of the Physical Education and Recreation, Agricultural, Life & Environmental Sciences and Native Studies Research Ethics Board (PER-ALES-NS REB), I am providing **research ethics approval** for your proposed research.

The research ethics approval is valid for one year and will expire on November 22, 2011.

A renewal report must be submitted prior to the expiry of this approval if your study still requires ethics approval at that time. If you do not renew before the renewal expiry date, you will have to re-submit an ethics application. If there are changes to the project that need to be reviewed, please file an amendment. If any adverse effects to human participants are encountered in your research, please contact the undersigned immediately.

Sincerely,

Kelvin Jones, Ph.D.
Chair, Physical Education and Recreation (PER), Agricultural Life & Environmental Sciences (ALES) and Native Studies (NS)

Note: This correspondence includes an electronic signature (validation and approval via an online system).

ID:Pro00016957

Status: Approved

1.1 Study Identification

*All questions preceded by a red asterisk * are required fields. Other fields may be required by the REB in order to evaluate your application.*
Please answer all presented questions that will reasonably help to describe your study or proposed research.

1.0 * **Short Study Title** *(restricted to 250 characters)*:
Relative Intensity of Muscular Effort during Multi-Joint Movement

2.0 * **Complete Study Title** *(can be exactly the same as short title)*:

Relative Intensity of Musclular Effort during Multi-Joint Movement

3.0 * **Select the appropriate Research Ethics Board (***Detailed descriptions are available by clicking the HELP link in the upper right hand corner of your screen***):**
PER-ALES-NS

4.0 * **Which office requires notification of ethics approval to release funds or finalize the study contract?** *(It is the PI's responsibility to provide ethics approval notification to any office other than the ones listed below)*
University of Alberta - Research Services Office (RSO)

5.0 * **Name of Principal Investigator** *(at the University of Alberta, Covenant Health, or Alberta Health Services)***:**
Megan Bryanton

6.0 **Investigator's Supervisor** *(Required for graduate students and trainees NOT applying to the Health Research Ethics Board (HREB). The HREBs do not accept graduate students or trainees as Principal Investigators in an ethics application. Please enter your supervisor as the PI and yourself as a co-investigator in your application for HREB.*

Loren Chiu

7.0 * **Type of research/study:**
Graduate Student - Thesis, Dissertation, Capping Project

8.0 **Study Coordinators or Research Assistants:** People listed here can edit this application and will receive all HERO notifications for the study:

Name	Employer
Loren Chiu	PE Phys Ed and Recreation

9.0 **Co-Investigators:** People listed here can edit this application but do not receive HERO notifications unless they are added to the study email list:

Name	Employer
Loren Chiu	PE Phys Ed and Recreation

10.0 **Study Team** *(Co-investigators, supervising team, other study team members):* People listed here cannot edit this application and do not receive HERO notifications:

Last Name	First Name	Organization	Role	Phone	Email
Chizewski	Michael	University of Alberta	Graduate Student		
Moolyk	Amy	University of Alberta	Graduate Student		

1.3 Study Funding Information

1.0 * **Type of Funding:**

Grant (external to the institution)

If OTHER, provide details:

2.0 **Funding Source**

2.1 Select all sources of funding from the list below:

There are no items to display

2.2 If not available in the list above, write the Sponsor/Agency name(s) in full (you may add multiple funding sources):

View National Strength and Conditioning Association (NSCA)

3.0 **Location of funding source** *(required if study is funded)***:**

US

4.0 **RSO University-Managed Funding**

4.1 If your funds are managed by the Research Service Office (RSO), select the project ID and title from the lists below to facilitate release of your study funds. *(Not available yet)*

4.2 If not available above, provide all identifying information about the study funding:

Project ID	Project Title	Speed Code	Other Information
	There are no items to display		

1.4 Conflict of Interest

1.0 * **Are any of the investigators or their immediate family receiving any personal remuneration (including investigator payments and recruitment incentives but excluding trainee remuneration or graduate student stipends) from the funding of this study that is not accounted for in the study budget?**

Yes **No**

If YES, explain:

2.0 * **Do any of investigators or their immediate family have any proprietary interests in the product under study or the outcome of the research including patents, trademarks, copyrights, and licensing agreements?**

Yes **No**

3.0 Is there any compensation for this study that is affected by the study outcome?

Yes **No**

4.0 Do any of the investigators or their immediate family have equity interest in the sponsoring company? (This does not include Mutual Funds)

Yes **No**

5.0 Do any of the investigators or their immediate family receive payments of other sorts, from this sponsor (i.e. grants, compensation in the form of equipment or supplies, retainers for ongoing consultation and honoraria)?

Yes No

6.0 Are any of the investigators or their immediate family, members of the sponsor's Board of Directors, Scientific Advisory Panel or comparable body?

Yes No

7.0 Do you have any other relationship, financial or non-financial, that, if not disclosed, could be construed as a conflict of interest?

Yes **No**

If YES, explain:

Loren Chiu has received honoraria in the previous year for speaking engagements for the sponsoring organization. These speaking engagements are unrelated to the project. Loren is also an associate editor for the organization's scientific journal and a member of the research consortium, contributing to reviews of grant applications and abstracts submitted for the annual conference.

Important

If you answered YES to any of the questions above, you may be contacted by the REB for more information or asked to submit a Conflict of Interest Declaration.

1.5 Research Locations and Sites

1.0 * **List the locations of the proposed research, including recruitment activities. Provide name of institution or organization, town, or province as applicable** (e.g. On campus, Alberta public elementary schools, shopping malls, doctors' offices in Lesser Slave Lake and Lac La Biche, AHS facilities in Zone 5, post-secondary students at UBC, UA, UT, McGill and Dalhousie, internet websites, etc.)**:**
Biomechanics Laboratory W2-72 Van Vliet Centre

2.0 * **Indicate if the study will utilize or access facilities, programmes, resources, staff, students, specimens, patients or their records, at any of the sites affiliated wiht the following** *(select all that apply):*
Not applicable

List all facilities or institutions as applicable:

3.0 **If the study involves researchers in other institution(s), will ethics approval be sought from other institutions/organizations** *(eg. another university, Alberta Cancer Board, school district board, etc)***?**
Not Applicable (if this application is for a new study or a pre-existing non-clinical study)

If YES, provide a list:

Name
There are no items to display

2.1 Study Objectives and Design

1.0 **Proposed Start Date:**

01/11/2010

2.0 Date that you expect to start working with human participants:
01/11/2010

3.0 Date that you expect to finish working with human participants:
31/05/2011

4.0 * Provide a lay summary of your proposed research suitable for the general public *(restricted to approx. 300 words).* **If the PI is not affiliated with the University of Alberta, Alberta Health Services or Covenant Health, please provide institutional affiliation:**

Human movement involves tasks requiring multi-joint control. Multi-joint movements are influenced by several muscle groups, each of which may have different functions. Previously, it has been assumed that all muscles are working at the same intensity realtive to their maximum force generating ability. Recent evidence has contridicted this assumption and have rather observed that the contribution of a muscle group relative to its maximal force generating ability differs between muscles in the same task. Therefore, the role of an individual muscle groups during multi-joint movement is likely influenced by the relative intensity that the muscle is actived.

The squat is a commonly implemented exercise in strength and conditioning programs. Men and women that are highly skilled in performing the high-bar squat exercises will perform muscle strength assessments and squatting tasks. Squatting tasks will be assessed using motion analysis techniques. Relative effort levels of muscle groups will be assessed and it will determined if lack of strength in the knee extensors will affect squatting technique.

The methodologies of this proposal will allow us to examine how technique changes manifest as compensation strategies due to muscle weakness, fatigue, tightness and/or inability to activate muscles in a coordinate fashion. In that, this research is expected to be beneficial for strength and conditioning professionals

5.0 * Provide a description of your research proposal including study objectives, background, scope, methods, procedures, etc. *(restricted to approx. 1,000 words).* **Footnotes and references should not be included here. Research methods questions in Section 5 of this form will prompt additional questions and information.**

Rationale for Project

Human movement involves tasks requiring multi-joint control. Multi-joint movements are influenced by several muscle groups, each of which may have different functions. Their specific functions are indicated by inherent architectural differences such as muscle shape, fibre orientation, fibre type and their attachment locations on bones, all of which will affect force production and ranges of motions permitted. However, it is often assumed that all muscles are working at the same relative intensity as an evolutionary adaptive mechanism to minimize energy cost. Such assumptions contradict current evidence. Recent research has suggested that the contribution of a muscle group relative to its maximal force generating ability differs between muscles in the same task. This research demonstrates how differences in internal and external architecture of muscle in conjunction with segment position changes and movement of the task may depict the role of an individual muscle group during multi-joint movement and the relative intensity that the muscle is activated.

Statement of Purpose and Research Hypotheses

The purpose of this research project is to investigate muscular strength and multi-segment coordination as factors in squatting performance in men and women. This research will provide information that will be directly applied in the field of strength and conditioning.

It is hypothesized, based on prior research, that during heavy squatting exercise:

1. The knee extensors will be active at or near their maximum force generating capacity, while the hip extensors and ankle plantar-flexors will be active at a lower relative intensity than the knee extensors.

2. As load increases, compensatory mechanisms will manifest as changes in squatting technique due to increased contribution of the hip extensors.

3. Men and women will display differences in relative muscle effort due to inherent muscle architectural and neuromuscular differences with respect to gender. Specifically, men will display lower mechanical efforts in the knee extensors at each load.

In summary, since multi-joint movements involve several muscles of differing force generating abilities and activation levels, in order to understand multi-joint coordination, relative intensity of muscle actions must first be determined. This study will investigate the squat task in order to determine the relative intensity of muscle activation.

Methods

Men and women of the university community will be recruited for this investigation. Based on prior investigationg, a sample size of 10 men and 10 women will be required to test for significant differences in relative intensity levels between muscle groups.

Participants will perform muscle strength assessments and squatting tasks. The muscular strength assessments will involve maximum voluntary isometric contractions of the hip extensors, knee extensors and ankle plantar-flexors. For squats, reflective markers will be placed on participants and recorded using 3D motion analysis system. Squats will be perfomred on force platforms and the force and motion analysis will be used to calculate net joint kinetics. Squats at 70%, 80% and 90% of the particiants 1 repitition maximum will be performed. In summary, data collection and analysis will:

1. Assess the muscular force of the hip, knee and ankle joints during the squat movement by assessing the segmental mechanics and interactions between each limb segment of the lower extremities.

2. Determine hip extensor, knee extensor and ankle plantar-flexor effort levels relative to their maximum force generating ability.

3. Assess the influence of increasing load and gender on muscular effort of the ankle plantar-flexors and the hip and knee extensors.

6.0 Describe procedures, treatment, or activities that are above or in addition to standard practices in this study area *(eg. extra medical or health-related procedures, curriculum enhancements, extra follow-up, etc)***:**
N/A

7.0 If this research proposal has received independent scientific or methodological review, provide information *(eg. names of committees or individuals involved in the review, whether review is in process or completed, etc)***:**
Supervisory Committee Members: Dr. Loren Chiu, Dr. Mike Kennedy, Dr. Jason Carey (review process completed)

8.0 If this application is related to or builds upon a previously approved application at the University of Alberta, please provide the study title and ethics file/approval number or any other reference if available:
N/A

3.1 Risk Assessment

1.0 *** After reviewing the Minimal Risk Criteria provided in User Help, provide your assessment of the risk classification for this study:**
Minimal Risk

2.0 *** In a scale of 0 to 10 where 0 = No Likelihood, 5 = Moderate Likelihood and 10 = Extreme Likelihood, put a numerical rating in response to each of the following:**

Rate	Description of Potential Risks and Discomforts
0	Psychological or emotional manipulations will cause participants to feel demeaned, embarrassed, worried or upset
2	Participants will feel fatigued or stressed
0	Questions will be upsetting to the respondents
0	Participants will be harmed in any way
0	There will be cultural or social risk – for example, possible loss of status, privacy, and/or reputation
2	There will be physical risk or physiological manipulations, including injury, infection, and possible intervention side-effects or complications
0	The risks will be greater than those encountered by the participants in everyday life

3.0 *** Provide details of short- and long-term risks and discomforts:**
As with any exercise there is risk of muscle strain and delayed onset muscle soreness.

4.0 *** Describe how you will manage and minimize risks and discomforts, as well as mitigate harm:**
The risks are expected to be minimal as the inclusion criteria for participants requires experience in performing the exercises involved. Therefore, the risk is not greater than what they would typically encounter when performing an exercise session. All exercise will be supervised by experienced trainers to ensure all exercise is performed appropriately.

5.0 *** If your study has the potential to identify individuals that are upset, distressed, or disturbed, or individuals warranting medical attention, describe the arrangements made to try to assist these individuals. Explain if no arrangements have been made:**
N/A

3.2 Benefits Analysis

1.0 **Describe any potential benefits of the proposed research to the participants. If there are no benefits, state this explicitly:**
Participants will be provided with feedback on their squatting performance. Participants will aslo be given feedback on the strength of their hip extensors, knee extensors and ankle plantar-flexors.

2.0 * **Describe the scientific and/or scholarly benefits of the proposed research:**
This proposed research will be one of the first to investigate multi-joint muscle effort levels during a high intensity strength training task such as the squat. This research will identify how strength influences skill and the resultant effects on squatting performance. In turn, it will further our understanding of muscle coordinative patterns during human movement when subject to different external demands.

3.0 **Describe any benefits of the proposed research to society:**
The experimental methodology is important for future study of multi-joint movement, in particular identifying how different muscles contribute to task performance. This methodology will be applicable in future studies on exercise effectiveness in strength and conditioning training and rehabilitative programs.

4.0 **Benefits/Risks Analysis: Describe the relationship of benefits to risk of participation in the research:**
Participants will be selected as previously being highly skilled in performing the squat exercise as a part of their regular strength and conditioning programs. Therefore, the benefits of being provided feedback on squat performance will outweight any potential risks as they are already comfortable performing the task at high intensities.

4.1 Participant Information

1.0 **Describe and justify the inclusion criteria for participants (eg. age range, health status, gender, etc):**

Men and women of ages 18-40 will be recruited to participate in this investigation. Inclusion criteria are:

1. Participants must have at least one year prior experience participating in heavy resistance exercise, including performing the high-bar squat. This is to ensure that participants are skilled in performing the exercises required and to minimize risk.

2. Men must be able to squat 1.5 times their body weight and females, 1.0 times their body weight. These requirements have been used previously to identify a strength-trained population. For this investigation, the homogeneity of a strength-trained population is desired.

2.0 **Describe and justify the exclusion criteria for participants:**

1. Individuals with a current or previous axial skeleton or lower extremity musculoskeletal injury that would prevent them from performing the squat exercise safely. Previous research has demonstrated that individuals with current or prior musculoskeletal injuries that have not been resolved perform multi-joint exercise such as the squat differently than otherwise healthy individuals.

2. Individuals with neurologic disorder. Individuals with neurologic disorders often present with muscle weakness, which may affect their ability to perform the exercises.

3.0 Are there any direct recruitment activities for this study?

◉ ◉ **Yes** ○ ○ No

4.0 Participants

Total number of participants you expect to enroll *(including controls, if applicable)***:**
20
Of these how many are controls, if applicable *(Possible answer: Half, Random, Unknown, or an estimate in numbers, etc).*
0
If this is a multi-site study, how many participants *(including controls, if applicable)* **do you anticipate will be enrolled in the entire study?**

5.0 Justification for sample size:
10 male and 10 female subjects will be recruited. This sample size allows detection of with-in subject effect size differences of 0.2 standard deviation (small difference) while minimizing type I error to 5% and type II error to 20% (Power = 80%).

6.0 If possible, provide expected start and end date of the recruitment/enrollment period:
Expected Start Date: 01/10/2010
Expected End Date: 31/05/2011

4.2 Recruit Potential Participants

1.0 Recruitment

1.1 Will potential participants be recruited through pre-existing relationships with researchers *(eg. employees, students, or patients of research team, acquaintances, own children or family members, etc)***?**

◉ ◉ **Yes** ○ ○ No

1.2 If YES, identify the relationship between the researchers and participants that could compromise the freedom to decline (eg. professor-student). How will you ensure that there is no undue pressure on the potential participants to agree to the study?
Students may be recruited for this investigation through announcements in courses. To prevent pressure on potential participants, an investigator who is not the instructor for the course will make the announcement and complete the informed consent process.

2.0 Outline any other means by which participants could be identified *(eg. response to advertising such as flyers, posters, ads in newspapers, websites, email, listservs; pre-existing records or existing registries; physician or community organization referrals; longitudinal study, etc)***:**
Flyers/posters, e-mail, announcement in FPER courses

4.3 Recruitment Contact Methods

1.0 How will initial contact be made? Select all that apply:

Potential participants will contact researchers
Researchers will contact potential participants

2.0 If contact will be made through an intermediary *(including snowball sampling)*, **select one of the following:**

3.0 If contact will be made through an intermediary, explain why the intermediary is appropriate and describe what steps will be taken to ensure participation is voluntary:

4.0 Provide the locations where participants will be recruited, *(i.e. educational institutions, facilities in Alberta Health Services or Covenant Health, etc)***:**
University of Alberta, Grant McEwan, NAIT, Alberta Weightlifting Association clubs

4.4 Informed Consent Determination

1.0 * Describe who will provide informed consent for this study (select all that apply):

All participants will be competent to give informed consent

2.0 How is consent to be indicated and documented? Select all that apply:

Signed consent form

3.0 What assistance will be provided to participants, or those consenting on their behalf, who have special needs *(eg non-English speakers, visually impaired, etc)***:**
This investigation will require participants to be physically active individuals who are involved in a free weight resistance training program. Because of our participant criteria, we do not anticipate recruiting participants who have sepcial needs.

4.0 If at any time a participant wishes to withdraw, end, or modify their participation in the research or certain aspects of the research, describe the procedures and the last point at which it can be done:
Participants will be informed that they can withdraw at any point during the investigation. As the investigation involves only 3 session, they will be informed that if they wish to stop participating, they need to inform the investigator at the time and the session will be terminated.

5.0 Describe the circumstances and limitations of data withdrawal from the study, including the last point at which it can be done:
Participants must complete the entire data collection protocol for the data to be used. Participants will be informed that their data will not be withdrawn if they have completed the data collection session.

6.0 **Will this study involve any group(s) where non-participants are present? For example, classroom research might involve groups which include participants and non-participants.**

Yes **No**

7.0 **Describe the incentives and/or reimbursements, if any, to participants and provide justification:**

4.8 Study Population Categories

1.0 * **This study is designed to TARGET or specifically include the following** *(does not apply to co-incidental or random inclusion)*. **Select all that apply:**

Women
Men

5.1 Research Methods and Procedures

Some research methods prompt specific ethic issues. The methods listed below have additional questions associated with them in this application. If your research does not involve any of the methods listed below, ensure that your proposed research is adequately described in Section 2.0: Study Objectives and Design or attach documents in Section 7.0 if necessary.

1.0 * **This study will involve the following** *(select all that apply)*
The list only includes categories that trigger additional page(s) for an online application. For any other methods or procedures, please indicate and describe in your research proposal in the Study Summary, or provide in an attachment:

Sound or image data involving participants (other than audio or video-recorded interviews or focus groups)

2.0 **Is this study a Clinical trial?** *A clinical trial is any research study that prospectively assigns human participants or groups of humans to one or more* ***health-related intervention(s)*** *to evaluate the effects on* ***health outcomes;*** *does not include randomized controlled trials – RCT – outside of clinical settings)?*

Yes **No**

3.0 **For registered clinical trial(s), provide registry and registration number, if available:**

4.0 **Internet-based research**

4.1 Will you be doing any internet-based research that involves interaction with participants?

○ ○ Yes ◉ ◉ **No**

4.2 If YES, will these interactions occur in private spaces (eg. members only chat rooms, social networking sites, email discussions, etc)?

○ ○ Yes ○ ○ No

4.3 Will these interactions occur in public space(s) where you will post questions initiating and/or maintaining interaction with participants?

○ ○ Yes ○ ○ No

5.0 If you are using any tests in this study diagnostically, indicate the member(s) of the study team who will administer the measures/instruments:

Test Name	Test Administrator	Organization	Administrator's Qualification
	There are no items to display		

6.0 If any test results could be interpreted diagnostically, how will these be reported back to the participants?

5.6 Sound or Image (other than audio- or video-recorded interviews) or Material Created by Participants

1.0 Explain if consent obtained at the beginning of the study will be sufficient, or if it will be necessary to obtain consent at different times, for different stages of the study, or for different types of data:

This investigation requires only 3 data collection sessions. However, in the case of exemplar performance, it may be desirable to use video data in a publication or presentation. In this case, consent from the individual will be obtained.

2.0 If you or your participant's audio- or video-records, photographs, or other materials artistically represent participants or others, what steps will you take to protect the dignity of those that may be represented or identified?

The video data used for this investigation will record reflective markers placed on the participants body. This video data cannot be used to identify an indidual. A standard digital video camera will be used in the case that abnormal data is obtained, from which the standard digital video record can be used to determine the source of the abnormality. These videos will be stored on password protected computers and hard drives. All video files will be stored using participant alpha-numeric codes and not names. Furthermore, each standard digital video file will be individually password protected. Therefore, even if an individual was able to gain access to the digital file, they would not be able to open the file. The standard digital video file is only necessary until data are processed. Once data have passed the processing stage, the files will be deleted, except in the case of 4.0 below.

3.0 Who will have access to this data? For example, in cases where you will be sharing sounds, images, or materials for verification or feedback, what steps will you take to protect the dignity of those who may be represented or identified?

Only the principal investigator and co-investigators will have access to this data.

4.0 When publicly reporting data or disseminating results of your study (eg presentation, reports, articles, books, curriculum material, performances, etc) that include the sounds, images, or materials created by participants you have collected, what steps will you take to protect the dignity of those who may be represented or identified?
In the case of exemplar performance, where the standard digital video data may be used in a publication or presentation, the participant will be contacted. The video will be shown to the participant, the manner in which the video will be used (i.e. publication or presentation) will be explained and the participant will be asked to provide written consent.

5.0 What opportunities are provided to participants to choose to be identified as the author/creator of the materials created in situations where it makes sense to do so?

6.0 If necessary, what arrangements will you make to return original materials to participants?

6.1 Data Collection

1.0 * Will the researcher or study team be able to identify any of the participants at any stage of the study?
(•) (•) **Yes** ( ) ( ) No

2.0 Primary/raw data collected will be *(check all that apply)*:

Directly identifying information-the information identifies a specific individual through direct identifiers (e.g. name, social insurance number, personal health number, etc.)
Indirectly identifying information-the information can reasonably be expected to identify an individual through a combination of indirect identifers (eg date of birth, place of residence, photo or unique personal characteristics, etc)
All personal identifying information removed

3.0 If identifying information will be removed at some point, when and how will this be done?
All data will be electronically stored. Participant codes will be assigned at enrollment and these codes will be used in file names. Participants names will not be associated with these data files.

4.0 If this study involves secondary use of data, list all original sources:
N/A

5.0 In research where total anonymity and confidentiality is sought but cannot be guaranteed *(eg. where participants talk in a group)* **how will confidentiality be achieved?**
N/A

6.2 Data Identifiers

1.0 * **Personal Identifiers:** will you be collecting any of the following *(check all that apply)***:**

Full Name
Initials
Telephone Number
Email Address
Year of Birth

If OTHER, please describe:

2.0 **Will you be collecting any of the following** *(check all that apply)***:**

There are no items to display

If OTHER, please describe:

3.0 **If you are collecting any of the above, provide a comprehensive rationale to explain why it is necessary to collect this information:**
Names, telephone numbers and e-mail addresses will be required if we need to contact the participants. Date of birth will be required to verify participants are of appropriate age as per inclusion criteria.

4.0 **Specify what identifiable information will be RETAINED once data collection is complete, and explain why retention is necessary. Include the retention of master lists that link participant identifiers with de-identified data:**
Names and contact information will be retained following data collection if it is necessary to contact individuals in the future. This information will not be linked to the data collected in the investigation.

5.0 **If applicable, describe your plans to link the data in this study with data associated with other studies (e.g within a data repository) or with data belongong to another organization:**

6.3 Data Confidentiality and Privacy

1.0 * **How will confidentiality of the data be maintained? describe how the identity of participants will be protected both during and after research.**
All data will be electronically stored in password protected computers and hard drives. Only the study investigators will have access to these passwords.

2.0 **What privacy education/training do members of the team have prior to their access to data? How will those who have access to the data be made aware of their responsibilities concerning privacy and confidentiality?**

The principal investigator has received ethic training as part of her coursework and from the facutly co-investigator. The faculty co-investigator has completed human subjects ethic training as part of his graduate training. Other study team members have received ethics training from the faculty co-investigator.

3.0 If you involve colleagues, assistants, transcribers, interpreters and/or other personnel to carryout specific research tasks in your study, how will you ensure that they properly understand and adhere to the University of Alberta standards of data privacy and confidentiality?
N/A

4.0 Data Access

*** 4.1 Will <u>identifiable</u> data be transferred or made available to persons or agencies outside of the research team?**

○ ○ **Yes** ◉ ◉ **No**

4.2 If YES, describe in detail what identifiable information will be released, to whom, why they need access, and under what conditions? What safeguards will be used to protect the identity of subjects and the privacy of their data.

4.3 Provide details if identifiable data will be leaving the institution, province, or country *(eg. member of research team is located in another institution or country, etc.)*

6.4 Data Storage, Retention, and Disposal

1.0 Describe how research data will be stored, e.g. digital files, hard copies, audio recordings, other? Specify the physical location and how it will be secured to protect confidentiality and privacy. (For example, study documents must be kept in a locked filing cabinet and computer files are encrypted, etc.)
Sport Biomechanics Laboratory - W2-72 Van Vliet Centre
P-320Q Van Vliet Centre [PI's office]
GB-05 Education [Graduate students office]
All data will be stored on password protected computers and hard drives.

2.0 If you plan to destroy your data, describe when and how this will be done. Indicate your plans for the destruction of the identifiers at the earliest opportunity consistent with the conduct of the research and/or clinical needs:
Motion analysis data will be retained indefinitely. This data will be used to construct a database for performance of jumping. No identifiers are included in this data. Standard digital video data will be destroyed after 5 years, except in the case of exemplar performance and data is used in publications or presentations. Consent will be obtained from the participant(s) to retain this data. In addition, Physical Activity and Medical History Questionnaire documents will be shredded from subjects who are screened but deemed ineligible for the study.

3.0 You must keep your data for a minimum of 5 years according to GFC Policy 96.2. How will you provide for data security during this time?
All data will be stored on password protected computers and hard drives.

7.1 Documentation

Add documents in this section according to the headers. Use Item 12.0 "Other Documents" for any material not specifically mentioned below.

Sample templates are available in the HERO Home Page in the ***Forms and Templates****, or by clicking HERE.*

Important: Please do not use .docx files as attachments. It is recommended you convert these files first to .doc (standard Word document files) before attaching.

1.0 Recruitment Materials:

Document Name	Version	Date	Description
Participant Recruitment Poster | History	0.01	04/09/2010 4:39 PM	

2.0 Letter of Initial Contact:

Document Name	Version	Date	Description
	There are no items to display		

3.0 Informed Consent / Information Document(s):

3.1 What is the reading level of the Informed Consent Form(s):
High School Reading Level

3.2 Informed Consent Form(s)/Information Document(s):

Document Name	Version	Date	Description
Video release.pdf | History	0.02	22/11/2010 7:29 PM	
Information Letter.doc | History	0.04	12/10/2010 3:29 PM	
Informed Consent.doc | History	0.01	03/09/2010 1:05 PM	

4.0 Assent Forms:

Document Name	Version	Date	Description
	There are no items to display		

5.0 Questionnaires, Cover Letters, Surveys, Tests, Interview Scripts, etc.:

Document Name	Version	Date	Description
Physical Activity and Medical History.doc | History	0.01	03/09/2010 7:57 PM	

6.0 Protocol:

Document Name	Version	Date	Description
	There are no items to display		

7.0 Investigator Brochures/Product Monographs *(Clinical Applications only)***:**

Document Name	Version	Date	Description
	There are no items to display		

8.0 Health Canada No Objection Letter *(NOL)***:**

Document Name	Version	Date	Description
	There are no items to display		

9.0 Confidentiality Agreement:

Document Name	Version	Date	Description
	There are no items to display		

10.0 Conflict of Interest:

Document Name	Version	Date	Description
	There are no items to display		

11.0 Other Documents:

For example, Study Budget, Course Outline, or other documents not mentioned above

Document Name	Version	Date	Description
	There are no items to display		

Final Page

You have completed your ethics application! Please select "Exit" to go to your study workspace.

This action will NOT SUBMIT the application for review.

Only the Study Investigator can submit an application to the REB by selecting the "SUBMIT STUDY" button in My Activities for this Study ID:Pro00016957.

You may track the ongoing status of this application via the study workspace.

Please contact the REB Administrator with any questions or concerns.

UNIVERSITY OF ALBERTA
Faculty of Physical Education and Recreation
E488 Van Vliet Centre
Edmonton, Alberta, Canada T6G 2H9

INFORMED CONSENT FORM

PROJECT TITLE: RELATIVE INTENSITY OF MUSCULAR EFFORT DURING MULTI-JOINT MOVEMENT

Principal Investigator: Megan Bryanton, Faculty of Physical Education and Recreation, 780-690-0057
Faculty Co-Investigator: Loren Chiu, PhD, Faculty of Physical Education and Recreation, 780-248-1263

Part 2 (to be completed by the research participant)

Do you understand that you have been asked to be in a research study?	Yes	No
Have you read and received a copy of the attached Information Sheet	Yes	No
Do you understand the benefits and risks involved in taking part in this research study?	Yes	No
Have you had an opportunity to ask questions and discuss this study?	Yes	No
Do you understand that you are free to refuse to participate, or to withdraw from the study at any time, without consequence, and that your information will be withdrawn at your request?	Yes	No
Has the issue of confidentiality been explained to you? Do you understand who will have access to your information?	Yes	No

This study was explained to me by: ____

I agree to take part in this study:

______________________________ ______________

Signature of Research Participant Date

____

Printed Name

______________________ ______________________

Witness Printed Name

I believe that the person signing this form understands what is involved in the study and voluntarily agrees to participate.

____________________________ ______________________

Signature of Investigator or Designee Date

The information sheet must be attached to this consent form and a copy of both forms given to the participant.

UNIVERSITY OF ALBERTA

Faculty of Physical Education and Recreation

E488 Van Vliet Centre
Edmonton, Alberta, Canada T6G 2H9

Neuromusculoskeletal Mechanics Research Program – Use of Video Release Form

I, _____________________, have consented to participate in the research project:

____.

I understand that digital video of me will be taken as part of the research protocol.

I hereby grant the Neuromusculoskeletal Mechanics Research Program and its staff permission to use digital videos taken of me for purposes of teaching and presentation.

I understand that, for purposes of teaching and presentation, such as digital videos may be accessible via the internet.

______________________________ ______________________________
Signature | Signature of Researcher/Study Team Member

______________________________ ______________________________
Date | Name of Researcher/Study Team Member

____
Date

UNIVERSITY OF ALBERTA
Faculty of Physical Education and Recreation
E488 Van Vliet Centre
Edmonton, Alberta, Canada T6G 2H9

INFORMATION LETTER

PROJECT TITLE: Relative Intensity of Muscular Effort during Multi-Joint Movement

INVESTIGATORS:

Loren Z.F. Chiu, PhD, CSCS
Assistant Professor

Amy Moolyk, B.Sc.
Megan Bryanton,BSc.
Graduate Students

Neuromusculoskeletal Mechanics Research Program
Faculty of Physical Education and Recreation
University of Alberta
Phone: 780-248-1263

PURPOSE:

The purpose of this investigation is to look at relative muscle effort levels of the hip extensors, knee extensors and ankle plantar flexors during a multi-joint squatting high-intensity exercise.

BACKGROUND:

The squat is a common resistance training exercise commonly implemented in strength and conditioning programs. A better understanding the extent to which muscles are working relative to their maximal force generating abilities influences squatting technique and can be used to increase performance and reduce risk of injury. For coaches and physical educators, it is important to identify unfavourable muscle compensation strategies due to muscle weakness for optimal performance and injury prevention. Men and women from the university community (ages 18-40) skilled in performing the squat will be recruited to participate in this study.

PROCEDURES:

Your participation will require 3 visits to the Sports Biomechanics Laboratory within a three-week span (i.e. sessions are spaced 1 week apart)

Session 1: Testing of one repetition maximum (1RM) in the high-bar back squat exercise. A parallel depth, where the top of the thigh at the inguinal fold descends below the top of the patella will be required. 1 RM testing procedures will involved increments in load until maximum has been achieved.

Session 2: The muscle force generation of your hip extensors, knee extensors and ankle plantar-flexors will be assessed using 3-D motion analysis and digital video recording. You will be asked to perform the high-bar squats at 70%, 80% and 90% of your previously determined 1 RM weight. Adequate rest intervals of 3-5 minutes will be allowed between sets to prevent any fatigue effects.

Reflective markers will be attached to your skin and clothes during sets. These markers will be recorded using motion analysis and digital video cameras while you perform the squat.

Session 3: The strength of you hip extensor, knee extensors and ankle-plantar flexors will assessed using computer-interfaced machines. You will be asked to contract your muscles as hard as possible during hip extension, knee extension and ankle-plantar flexion tasks.

The total time for each session will be approximately 1 hour.

UNIVERSITY OF ALBERTA

Faculty of Physical Education and Recreation

E488 Van Vliet Centre

Edmonton, Alberta, Canada T6G 2H9

INFORMATION LETTER

PROJECT TITLE: Relative Intensity of Muscular Effort during Multi-Joint Movement

BENEFITS:
If you participate, you will be provided with feedback on your squat technique. We will also provide feedback about the strength of your hip extensors, knee extensors and ankle-plantar flexors. This information can be used to improve squat strength and performance and decrease injury risk. The data for this study will also be used to provide coaches and physical educators information on how to improve strength and conditioning performance and decrease injury risk.

RISKS:
As with any physical activity, there is the potential for muscle or joint injury. These may include straining the muscles of the thigh and calf, and spraining the ligaments in the knee and ankle. These risks should be minimal as the tasks performed are similar to those you would regularly perform in a squatting practice.

CONFIDENTIALITY:
All information you provide and data collected will be confidential. All documents and files will be coded, and your name will not be attached to them. All documents will be stored in a locked room, and files on password protected computers and hard drives. When the study is presented or published, personal information that can be used to indentify you will not be included.

DATA STORAGE:
All data will be stored for a minimum of 5 years. As the data and video files are coded, your name will not be attached to the files. All files will be stored on password protected computers and hard drives.

FREEDOM TO WITHDRAW:
Your participation in this study is voluntary. If at any time you change your mind, you may withdraw from the study by verbally indicating to the investigators. If you withdraw, your personal information will be removed from the study.

ADDITIONAL CONTACTS:
If you have concerns about this study, you may contact Dr. Kelvin Jones, Acting Chair of the PER-ALES Research Ethics Board, at 780-492-0650. Dr. Jones has no direct involvement with this project.

APPENDIX B

SUBJECT CHARACTERISTICS DATA

Table B-1. Subject Characteristics Data

Subject	Age (yrs)	Height (cm)	Body Weight (kg)	Experience (yrs)	1RM (kg)
S1	27	151	52.5	10	80
S2	23	165	66.5	6	85
S3	24	162	55.5	5	75
S4	20	168	66	2	80
S5	22	170	59	4	70
S6	21	176	68	1	75
S7	23	174	58	4	90
S8	23	160	61	8	100
S9	20	171	64.5	1	65
S10	22	181	74	1	85

APPENDIX C

MAXIMUM ISOMETRIC DATA

Table C-1. Subject summed maximum isometric NJM values during ankle plantar-flexion with respect to ankle joint angle.

	Subject	Ankle Angle (degrees)		
		5	15	25
ANKLE	S1	59	73	118
NJM	S2	105	116	171
(Nm)	S3	73	96	126
	S4	68	103	92
	S5	107	121	131
	S6	108	141	169
	S7	94	115	117
	S8	86	104	117
	S9	103	122	137
	S10	131	151	173

Table C-2. Subject summed maximum isometric NJM values during knee extension with respect to knee joint angle

	Subject	Knee Angle (degrees)		
		30	60	90
KNEE	S1	109	158	196
NJM	S2	143	208	266
(Nm)	S3	141	221	262
	S4	191	307	313
	S5	161	249	265
	S6	148	269	308
	S7	109	164	194
	S8	131	204	261
	S9	164	250	256
	S10	149	232	308

Table C-3. Subject summed maximum isometric NJM values during hip extension with respect to hip joint angle

	Subject	Hip Angle (degrees)		
		30	60	90
HIP	S1	146	214	196
NJM	S2	157	193	237
(Nm)	S3	135	179	246
	S4	121	179	272
	S5	214	266	316
	S6	193	232	278
	S7	154	262	301
	S8	212	243	275
	S9	259	279	311
	S10	187	256	321

APPENDIX D:

SUBJECT MOTION DATA

Table D-1. Subject summed ankle plantar-flexor NJM values with respect to knee joint angle at 50% 1RM.

		Knee Angle (degrees)			
	Subject	30	60	90	105
ANKLE	S1	38	54	76	75
NJM	S2	59	98	89	92
(Nm)	S3	54	81	92	108
	S4	43	28	45	92
	S5	51	56	65	77
	S6	52	64	118	113
	S7	19	29	63	84
	S8	48	61	60	68
	S9	70	74	115	108
	S10	113	126	130	141

Table D-2. Subject summed ankle plantar-flexor NJM values with respect to knee joint angle at 60% 1RM.

		30 degrees	60 degrees	90 degrees	105 degrees
	Subject	Nm	Nm	Nm	Nm
ANKLE	S1	48	75	93	94
	S2	2	122	113	102
	S3	49	103	106	116
	S4	53	50	27	78
	S5	61	68	86	93
	S6	66	95	104	97
	S7	44	49	85	110
	S8	48	71	64	70
	S9	67	107	127	129
	S10	115	148	140	152

Table D-3. Subject summed ankle plantar-flexor NJM values with respect to knee joint angle at 70% 1RM.

		Knee Angle (degrees)			
	Subject	30	60	90	105
ANKLE	S1	1	60	96	102
NJM	S2	91	125	113	120
(Nm)	S3	51	80	116	133
	S4	57	96	56	101
	S5	70	88	118	116
	S6	74	113	130	120
	S7	49	68	83	107
	S8	89	109	76	91
	S9	69	128	140	128
	S10	136	146	163	155

Table D-4. Subject summed ankle plantar-flexor NJM values with respect to knee joint angle at 80% 1RM.

	Subject	Knee Angle (degrees)			
		30	60	90	105
ANKLE	S1	53	67	110	126
NJM	S2	90	171	136	147
(Nm)	S3	47	127	122	128
	S4	83	107	46	73
	S5	67	84	125	71
	S6	87	117	138	131
	S7	52	45	93	126
	S8	96	123	88	96
	S9	63	114	142	147
	S10	124	141	178	177

Table D-5. Subject summed ankle plantar-flexor NJM values with respect to knee joint angle at 90% 1RM.

	Subject	Knee Angle (degrees)			
		30	60	90	105
ANKLE	S1	25	58	116	128
NJM	S2	144	192	164	163
(Nm)	S3	54	128	131	139
	S4	66	128	54	72
	S5	73	91	124	126
	S6	124	149	157	144
	S7	90	88	122	148
	S8	99	126	113	129
	S9	88	144	147	143
	S10	158	181	187	189

Table D-6. Subject summed knee extensor NJM values with respect to knee joint angle at 50% 1RM.

	Subject	Knee Angle (degrees)			
		30	60	90	105
KNEE	S1	23	10	116	141
NJM	S2	56	145	162	171
(Nm)	S3	30	94	140	195
	S4	28	110	154	175
	S5	39	103	157	165
	S6	33	110	148	167
	S7	43	119	149	158
	S8	29	115	161	202
	S9	26	100	150	153
	S10	43	111	210	214

Table D-7. Subject summed knee extensor NJM values with respect to knee joint angle at 60% 1RM.

	Subject	Knee Angle (degrees)			
		Nm	Nm	Nm	Nm
KNEE	S1	22	94	115	147
NJM	S2	60	140	164	178
(Nm)	S3	26	117	138	206
	S4	33	122	157	202
	S5	34	101	159	176
	S6	20	120	180	178
	S7	35	123	159	173
	S8	40	131	165	212
	S9	16	121	161	155
	S10	31	128	219	221

Table D-8. Subject summed knee extensors NJM values with respect to knee joint angle at 70% 1RM.

	Subject	Knee Angle (degrees)			
		30	60	90	105
KNEE	S1	41	103	118	152
NJM	S2	68	163	175	188
(Nm)	S3	37	132	138	197
	S4	31	109	156	202
	S5	14	46	153	181
	S6	35	126	181	180
	S7	41	114	160	174
	S8	22	123	175	211
	S9	12	120	165	160
	S10	33	121	216	228

Table D-9. Subject summed knee extensors NJM values with respect to knee joint angle at 80% 1RM.

	Subject	Knee Angle (degrees)			
		30	60	90	105
KNEE	S1	38	103	121	163
NJM	S2	58	159	164	185
(Nm)	S3	35	163	145	226
	S4	28	120	173	209
	S5	34	106	159	172
	S6	35	134	192	184
	S7	36	135	170	182
	S8	34	131	178	209
	S9	28	144	169	154
	S10	55	151	226	238

Table D-10. Subject summed knee extensor NJM values with respect to knee joint angle at 90% 1RM.

	Subject	Knee Angle (degrees)			
		30	60	90	105
KNEE	S1	67	99	123	174
NJM	S2	57	168	165	196
(Nm)	S3	46	143	146	210
	S4	51	147	185	208
	S5	25	107	172	188
	S6	22	120	188	179
	S7	36	121	171	194
	S8	30	128	186	207
	S9	15	129	151	154
	S10	52	160	212	238

Table D-11. Subject summed hip extensors NJM values with respect to knee joint angle at 50% 1RM.

	Subject	Knee Angle (degrees)			
		30	60	90	105
HIP	S1	63	154	165	148
NJM	S2	20	62	95	130
(Nm)	S3	45	97	181	215
	S4	67	132	232	157
	S5	66	196	128	144
	S6	70	8	205	230
	S7	106	179	212	218
	S8	74	158	192	234
	S9	59	101	138	156
	S10	65	148	186	206

Table D-12. Subject summed hip extensor NJM values with respect to knee joint angle at 60% 1RM.

	Subject	Knee Angle (degrees)			
		30	60	90	105
HIP	S1	82	175	178	168
NJM	S2	28	81	121	145
(Nm)	S3	36	125	203	236
	S4	71	177	281	231
	S5	82	117	155	174
	S6	75	155	236	244
	S7	123	229	255	252
	S8	76	182	216	265
	S9	63	117	153	171
	S10	79	156	197	230

Table D-13. Subject summed hip extensors NJM values with respect to knee joint angle at 70% 1RM.

	Subject	Knee Angle (dgrees) 30	60	90	105
HIP	S1	103	193	191	180
NJM	S2	32	88	128	153
(Nm)	S3	68	162	228	268
	S4	65	188	256	315
	S5	120	146	189	212
	S6	86	157	246	261
	S7	150	254	264	256
	S8	96	224	227	288
	S9	64	139	176	192
	S10	84	185	254	264

Table D-14. Subject summed hip extensors NJM values with respect to knee joint angle at 80% 1RM.

	Subject	Knee Angle (degrees) 30	60	90	105
HIP	S1	153	224	211	212
NJM	S2	40	96	131	169
(Nm)	S3	41	142	253	285
	S4	71	193	267	317
	S5	99	139	197	187
	S6	102	172	266	286
	S7	172	277	286	280
	S8	114	232	263	303
	S9	75	143	193	208
	S10	80	171	268	308

Table D-15. Subject summed hip extensor NJM values with respect to knee joint angle at 90% 1RM.

	Subject	Knee Angle (dgrees) 30	60	90	105
HIP	S1	138	240	194	236
NJM	S2	51	92	156	197
(Nm)	S3	47	174	280	302
	S4	65	179	268	313
	S5	121	162	222	244
	S6	144	206	285	318
	S7	175	297	319	303
	S8	140	246	270	307
	S9	96	179	227	227
	S10	57	185	317	340

Table D-16. Ankle joint angle with respect to knee joint angle at 50% 1RM.

		Knee Angle (degrees)			
	Subject	**30**	**60**	**90**	**105**
Ankle Angle (degrees)	**S1**	10	21	29	34
	S2	17	28	35	35
	S3	14	26	34	36
	S4	8	18	24	27
	S5	11	23	34	38
	S6	10	22	28	30
	S7	7	19	29	33
	S8	11	21	29	30
	S9	13	25	35	37
	S10	16	28	40	44

Table D-17. Ankle joint angle with respect to knee joint angle at 60% 1RM.

		Knee Angle (degrees)			
	Subject	**30**	**60**	**90**	**105**
Ankle Angle (degrees)	**S1**	10	21	30	34
	S2	17	29	35	36
	S3	13	25	32	35
	S4	9	19	23	26
	S5	11	23	34	38
	S6	9	21	28	29
	S7	8	19	29	33
	S8	11	21	27	29
	S9	12	25	35	37
	S10	16	28	40	43

Table D-18. Ankle joint angle with respect to knee joint angle at 70% 1RM.

		Knee Angle (degrees)			
	Subject	**30**	**60**	**90**	**105**
Ankle Angle (degrees)	**S1**	8	18	29	33
	S2	15	26	35	37
	S3	12	23	32	34
	S4	10	20	25	28
	S5	8	21	32	36
	S6	11	21	28	29
	S7	10	20	30	35
	S8	10	20	28	30
	S9	12	25	34	36
	S10	16	27	38	41

Table D-19. Ankle joint angle with respect to knee joint angle at 80% 1RM.

	Subject	Knee Angle (degrees)			
		30	60	90	105
Ankle Angle (degrees)	S1	8	17	29	33
	S2	18	30	37	38
	S3	13	25	28	32
	S4	11	21	23	27
	S5	6	21	30	35
	S6	8	19	26	27
	S7	6	16	26	32
	S8	12	21	28	30
	S9	11	24	34	35
	S10	17	28	39	41

Table D-20. Ankle joint angle with respect to knee joint angle at 90% 1RM.

	Subject	Knee Angle (degrees)			
		30	60	90	105
Ankle Angle (degrees)	S1	7	15	28	32
	S2	19	31	37	37
	S3	12	23	28	33
	S4	12	23	24	26
	S5	8	22	31	34
	S6	8	17	25	25
	S7	7	17	27	33
	S8	11	21	29	33
	S9	11	24	32	34
	S10	17	28	36	39

Table D-21. Hip joint angle with respect to knee joint angle at 50% 1RM.

	Subject	Knee Angle (degrees)			
		30	60	90	105
Hip Angle (degrees)	S1	42	67	87	90
	S2	30	49	72	81
	S3	31	55	81	88
	S4	51	78	104	110
	S5	50	69	88	98
	S6	47	66	92	105
	S7	57	82	99	102
	S8	47	73	94	103
	S9	42	62	83	95
	S10	32	57	74	81

Table D-22. Hip joint angle with respect to knee joint angle at 60% 1RM.

	Subject	Knee Angle (degrees)			
		30	60	90	105
Hip Angle (degrees)	S1	41	67	86	90
	S2	29	50	72	82
	S3	30	58	83	88
	S4	48	75	105	110
	S5	51	71	89	99
	S6	48	70	95	107
	S7	55	81	100	102
	S8	47	73	96	103
	S9	53	70	89	95
	S10	31	53	74	80

Table D-23. Hip joint angle with respect to knee joint angle at 70% 1RM.

	Subject	Knee Angle (degrees)			
		30	60	90	105
Hip Angle (degrees)	S1	44	69	87	90
	S2	26	48	71	81
	S3	36	63	85	89
	S4	47	73	105	110
	S5	54	72	91	102
	S6	47	68	94	106
	S7	54	82	99	102
	S8	46	75	95	105
	S9	42	63	83	95
	S10	28	53	72	81

Table D-24. Hip joint angle with respect to knee joint angle at 80% 1RM.

	Subject	Knee Angle (degrees)			
		30	60	90	105
Hip Angle (degrees)	S1	45	74	88	91
	S2	29	48	71	80
	S3	34	58	87	91
	S4	44	70	104	109
	S5	50	68	87	95
	S6	45	67	93	105
	S7	55	83	100	102
	S8	46	73	96	104
	S9	42	61	83	95
	S10	30	52	71	81

Table D-25. Hip joint angle with respect to knee joint angle at 90% 1RM.

	Subject	Knee Angle (degrees)			
		30	**60**	**90**	**105**
Hip Angle (degrees)	**S1**	40	74	90	92
	S2	28	47	71	81
	S3	33	58	88	91
	S4	43	66	102	109
	S5	50	69	88	98
	S6	47	67	92	108
	S7	50	80	100	102
	S8	48	74	95	101
	S9	42	62	87	98
	S10	24	47	72	81

Table D-26. Leg segment angle with respect to knee joint angle at 50% 1RM.

	Subject	Knee Angle (degrees)			
		30	**60**	**90**	**105**
Leg Angle (degrees)	**S1**	12	23	31	35
	S2	19	30	37	38
	S3	16	29	36	38
	S4	9	19	24	28
	S5	14	27	39	45
	S6	13	25	35	37
	S7	7	19	29	33
	S8	12	22	30	32
	S9	13	26	37	40
	S10	18	29	42	46

Table D-27. Leg segment angle with respect to knee joint angle at 60% 1RM.

	Subject	Knee Angle (degrees)			
		30	**60**	**90**	**105**
Leg Angle (degrees)	**S1**	12	22	32	36
	S2	19	30	38	38
	S3	15	28	35	37
	S4	11	19	24	27
	S5	14	27	39	44
	S6	13	25	33	35
	S7	8	18	29	35
	S8	12	22	28	30
	S9	13	27	38	41
	S10	18	29	42	46

Table D-28. Leg segment angle with respect to knee joint angle at 70% 1RM.

		Knee Angle (degrees)			
	Subject	**30**	**60**	**90**	**105**
Leg	**S1**	10	20	31	35
Angle	**S2**	18	29	38	39
(degrees)	**S3**	13	25	33	35
	S4	11	21	26	28
	S5	12	25	39	43
	S6	14	25	35	37
	S7	8	18	28	33
	S8	13	23	30	31
	S9	13	27	38	40
	S10	18	29	40	44

Table D-29. Leg segment angle with respect to knee joint angle at 80% 1RM.

		Knee Angle (degrees)			
	Subject	**30**	**60**	**90**	**105**
Leg	**S1**	9	18	31	35
Angle	**S2**	20	32	39	40
(degrees)	**S3**	15	18	31	33
	S4	12	22	24	27
	S5	13	26	39	45
	S6	13	26	35	37
	S7	6	16	28	34
	S8	14	23	29	31
	S9	12	26	37	40
	S10	18	29	41	44

Table D-30. Leg segment angle with respect to knee joint angle at 90% 1RM.

		Knee Angle (degrees)			
	Subject	**30**	**60**	**90**	**105**
Leg	**S1**	8	17	30	35
Angle	**S2**	21	33	40	39
(degrees)	**S3**	15	16	30	32
	S4	14	24	26	27
	S5	12	25	38	42
	S6	14	25	35	35
	S7	8	18	29	35
	S8	13	23	31	32
	S9	12	25	35	38
	S10	19	31	39	43

Table D-31. Changes in COP from neutral standing position to maximum depth position with respect to load (negative denotes backwards shifting towards heels)

		Load (%1RM)				
	Subject	50%	60%	70%	80%	90%
Change in COP (cm)	S1	-3.7	5.81	-3.97	5.09	5.65
	S2	3.91	7.73	7.05	6.65	8.09
	S3	8.92	7.5	10.14	7.8	8.81
	S4	5.12	9.08	3.26	-0.11	4.78
	S5	5.57	6.29	9.94	11.39	8.45
	S6	12.76	5.52	6.76	9.68	6.76
	S7	8.5	5.84	8.49	8.47	6.23
	S8	-2.53	0.49	-0.63	1.54	-3.63
	S9	7.89	8.08	7.14	11.55	6.23
	S10	2.52	8.98	1.16	7.75	4.03