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# Lower extremity power and knee extensor rapid force development after knee injury, surgery, and rehabilitation

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# LOWER EXTREMITY POWER AND KNEE EXTENSOR RAPID FORCE DEVELOPMENT AFTER KNEE INJURY, SURGERY, AND REHABILITATION

by

Daniel Garrett Cobian

A thesis submitted in partial fulfillment
of the requirements for the Doctor of
Philosophy degree in Physical Rehabilitation Science
in the Graduate College of
The University of Iowa

December 2015

Thesis Supervisor: Associate Professor Glenn N. Williams

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The University of Iowa
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CERTIFICATE OF APPROVAL

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PH.D. THESIS

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This is to certify that the Ph.D. thesis of

Daniel Garrett Cobian

has been approved by the Examining Committee for
the thesis requirement for the Doctor of Philosophy degree
in Physical Rehabilitation Science at the December 2015 graduation.

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To Katy.  Thanks for coming to Iowa with me.

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“In science one tries to tell people, in such a way as to be understood by everyone, something that no one ever knew before. But in poetry, it's the exact opposite.”

- Paul A.M. Dirac

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# ACKNOWLEDGEMENTS

As I typed the names of my committee members into the Certificate of Approval page of this document, I experienced a wave of both joy and appreciation. I feel extremely lucky to be able to refer to these individuals as my thesis committee members. Dr. Glenn Williams has been decisively in my corner from Day 1 and has contributed immensely to my growth as a researcher, writer, and scientist. Under his direction, I feel I have truly learned how to do things "the right way." I hope to go forth using all he has taught me and make strong contributions to our field while maintaining a rigorous standard of sifting and winnowing.

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understanding and promoting the importance of evidence based medicine. The feedback they have provided in regards to this work has been both prescient and grounded. Despite the multitude of clinical and academic obligations, they have been more than willing to donate their time and expertise to these projects.

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# ABSTRACT

Typical rehabilitation strategies and performance tests after knee surgery are often based on peak lower extremity strength.  However, people rarely generate maximal knee force in both daily and sports activities, which are characterized by brief periods of rapid muscle activation and relaxation. Thus, the ability to rapidly develop or modulate force may be more meaningful and more relevant to function. It is unclear how knee surgery influences the neuromuscular mechanisms controlling the ability to rapidly develop leg muscle force and produce power, or the functional relevance of these characterizations of muscle performance in relation to injury, surgery, and recovery.

The primary purpose of this collection of studies was to assess rapid quadriceps muscle activation and lower extremity force production in people undergoing arthroscopic knee surgery for meniscal debridement and anterior cruciate ligament (ACL) reconstruction.

People undergoing arthroscopic partial meniscectomy (APM) presented with significant deficits in knee extensor rate of torque development (RTD), leg press power, and rapid quadriceps muscle activation both prior to and in the initial month following surgery.  Subjective knee function was significantly correlated with RTD variables but not with peak strength or quadriceps volume.  Limitations in the ability to rapidly activate the involved quadriceps suggests that impaired centrally mediated neural function of the involved quadriceps may limit RTD and lower extremity power post-surgery.

Next, the speed and intensity of quadriceps exercise performed in the early post-surgical period of patients post-APM and the relationships between training parameters, strength, quadriceps RTD, and subjective knee function were investigated.  Subjects

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performed high intensity quadriceps contractions 2-3x/week in the first month following surgery. All subjects increased quadriceps strength, but people who trained with greater RTD following APM demonstrated greater improvements in RTD and had better patient-based outcomes scores than those who trained with a slower rate of torque rise.

Finally, power and rate of force development (RFD) in people ≤ 1 year following ACL reconstruction were evaluated along with movement biomechanics, typical clinical measures of readiness to return to activity, and patient-based outcomes. Significant side-to-side asymmetries in quadriceps strength, RFD, leg press strength and power, and knee joint kinetics were noted. Deficits in voluntary quadriceps strength paralleled the deficits in early phase RFD, indicating that in this population RFD was limited by the intrinsic properties and force production capacity of the quadriceps, not the ability to rapidly activate the muscle. However, strong to very strong correlations were found between quadriceps RFD, movement biomechanics and subjective knee function, which were predominantly stronger than the correlations with peak quadriceps strength. Leg press strength, power, and acceleration were very strongly correlated with movement biomechanics and subjective knee function.

In summary, this series of studies provides important insight into the neuromuscular mechanisms related to rapid lower extremity force development and muscle activation in the context of knee joint injury and recovery after arthroscopic knee surgery. Collectively, this work suggests that the inability to quickly develop or modulate quadriceps force may have significant functional consequences, and that rehabilitation efforts following arthroscopic knee surgery to incorporate both specific dosage of and earlier performance of rapid leg muscle contractions should be explored.

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# PUBLIC ABSTRACT

The treatment of knee joint injury, from diagnosis to surgery and rehabilitation, has improved dramatically over the last 30 years. Today, we are able to do amazing things to help people return to their desired activities after severe knee joint injury. Despite our advances in the understanding of human physiology and use of technology, people present with abnormal muscle performance and function long after knee surgery. Movement patterns can be abnormal even after extensive rehabilitation and training. Ultimately, these issues may lead to early development of osteoarthritis and reduced quality of life. As scientists and clinicians, we must ask how we can do a better job of targeting the specific deficits in neuromuscular function and ultimately, improve recovery.

Typical human movement involves patterns of rapid muscle activation and relaxation, or rapid increases and decreases in submaximal force production. Yet, post-surgical rehabilitation strategies are characterized by a gradual progression of slow sustained contractions, which, when coupled with the lack of activity during this protected period, may result in significant deficits in the ability to rapidly produce leg muscle force, which could negatively affect function. The focus of this work was to examine the neuromuscular determinants of rapid force production and leg power after knee injury and surgery, and evaluate the potential importance of these measurements in relation to movement biomechanics and subjective outcomes. The results of these studies indicate that limitations in rapid force development, muscle activation, and/or power have functional implications, and that we should consider altering treatment strategies to help people live happier and healthier lives after knee injury or surgery.

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# CHAPTER 1

# INTRODUCTION

Physical therapists are human movement specialists who prescribe therapeutic interventions to restore or improve function, mobility, and quality of life for people with a variety of musculoskeletal, neurologic, cardiovascular, and other pathological conditions. The proper prescription of physical therapy interventions requires a comprehensive understanding of the causes and results of injury, disease, and impairment, and knowledge of the expected physiologic response to the prescribed treatment.

In orthopaedic settings, physical therapists prescribe specific exercise interventions in an attempt to normalize and/or improve neuromuscular performance following disease, injury, or surgery. Physical therapy intervention related to knee injury and surgery typically involves exercises to improve ROM, strengthen the leg muscles (preferentially the quadriceps, which is characteristically affected by knee joint pathology)(Eitzen et al., 2010, Palmieri-Smith et al., 2008, Stevens et al., 2003), and assist in returning patients to their previous levels of function for successful performance of daily and/or athletic activities.

Although arthroscopic knee surgery produces satisfactory clinical outcomes (Petty and Lubowitz, 2012, Spindler et al., 2011, Westermann et al., 2014), recent in depth investigations indicate that patients struggle to return to previous levels of athletic activity (Ardern et al., 2012, Ardern et al., 2014, Ardern et al., 2011) and present with abnormal quadriceps muscle performance (Krishnan and Williams, 2011, Palmieri-Smith et al., 2008) and movement biomechanics (Hall et al., 2015, Hart et al., 2010a, Noehren et al., 2013, Stearns and Pollard, 2013) years after surgery. The inability to successfully restore lower extremity function can

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have significant consequences. Kinematic changes at the knee joint result in diminished load attenuation and/or altered loading parameters, which could be a contributing factor to development and/or progression of osteoarthritis.(Andriacchi and Mundermann, 2006, Bennell et al., 2013, Herzog and Longino, 2007) Premature degradation of knee joint cartilage is associated with significantly diminished quality of life (Farr Ii et al., 2013) and the prospect of future knee surgery and/or significant health care costs.(Losina et al., 2015, Wright et al., 2010)

Aberrant movement patterns following knee surgery can persist even after side to side asymmetries in quadriceps strength have dissipated (Roewer et al., 2011), which implies that we may be missing something in our evaluation and understanding of the effects of trauma on the neuromuscular system. Long term biomechanics data and sustained neuromuscular performance deficits suggest that we as physical therapists can do a better job of helping people successfully recover from knee injury and surgery. To do so, we must fully understand the changes in the neuromuscular system related to knee joint and pathology and prescribe interventions which are specifically and appropriately dosed to target the observed deficits.

Standard rehabilitation following knee injury/surgery begins with low intensity exercises, such as quadriceps setting or straight leg raises performed with slow ramp contractions.(Meier et al., 2008, O'Connor and Jackson, 2001, Wilk et al., 2012) As a result of injury or surgery, people become more sedentary and are more protective of the injured limb.(Roos et al., 2000) This disuse contributes to neuromuscular system dysfunction. (Horstman et al., 2012, Rutherford et al., 1990) The combination of knee joint pathology, surgical intervention, changes in patient behavior/activity levels, and the typical physical therapy regimen following knee injury/surgery may contribute to neuromuscular system dysfunction related to the ability to rapidly generate quadriceps force.

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This is an important concept as the majority of human movements require alternating periods of rapid muscle activation and relaxation. Analysis of electromyography (EMG) data collected during common activities such as walking or stepping indicates that human movement patterns are characterized by short periods of time in which muscles are rapidly activated (thus rapidly developing contractile force) to produce the desired outcome.(Cappellini et al., 2006, Gazendam and Hof, 2007, Gross et al., 1998, Rand and Ohtsuki, 2000, Sung and Lee, 2009) An inability to rapidly modulate muscle force may result in performance decrements.

Conversely, objective measurements of muscle performance in the fields of strength and conditioning (Peterson et al., 2004), human physiology (Enoka, 1988), and rehabilitation (Palmieri-Smith et al., 2008) are often focused on the peak force generating capability of a muscle. Peak force measurements are time-independent. Measuring muscle power, the rate of muscle activation, or force generation creates time-dependent characterizations of performance that may more closely resemble how muscles activate, contract, and relax to allow people to perform typical daily activities.(Martin, 2007) Evaluating peak strength may help define what a muscle is capable of, but may lack specificity in characterizing muscle performance beyond a threshold level. Measures of contractile rate of force development (RFD), rapid muscle activation, and muscle power may provide more specific insights into the neuromuscular determinants of human performance.

## Neuromuscular Mechanisms of Rapid Force Production

### Neural factors influencing RFD/Power

The ability to rapidly develop contractile force is controlled by an array of neural and structural factors. Absolute values of power and RFD are strongly moderated by the maximal force generating capacity of the muscle.(Aagaard et al., 2002a, Andersen et al., 2010)

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Normalizing RFD to peak force allows comparisons of the rate of force rise independent of muscle strength. Recent evidence indicates that the primary determinants of RFD vary throughout the contraction period.(Folland et al., 2014) Early phase (0 – 50 ms) normalized RFD is primarily controlled by agonist neural drive (Tillin et al., 2012), as a result of motor unit firing frequency, doublet discharges (increasing sarcoplasmic reticulum calcium release (Cheng et al., 2013)), or changes in motor unit recruitment patterns.(Aagaard et al., 2002a, Barry et al., 2005, Duchateau and Baudry, 2014, Hakkinen et al., 1985, Van Cutsem et al., 1998) Although intrinsic contractile properties of the quadriceps muscle are similar between explosive power athletes and moderately trained control subjects, athletes present with significantly greater voluntary normalized RFD due to differences in neural activation.(Tillin et al., 2010) Elevated V-wave and H-reflex responses following a period of strength training correlate with improvements in rapid force production (Holtermann et al., 2007a) and reflect possible increases in motoneuron excitability and/or decreases in presynaptic inhibition.(Aagaard et al., 2002c)

Improved muscle coordination, or reduced co-activation of antagonist muscles during rapid voluntary efforts, could positively influence RFD. Training studies indicate decreases in antagonist co-activation are related to improved force production (Carolan and Cafarelli, 1992), and athletes exhibit less antagonist activation during voluntary efforts when compared to sedentary individuals.(Amiridis et al., 1996) Explosive strength training may result in increased antagonist reciprocal inhibition at the initiation of contraction.(Geertsen et al., 2008)

Neural adaptations influencing RFD have been reported following a single session of explosive strength training (Peterson, 2009, Selvanayagam et al., 2011), and multiple investigations have noted concurrent improvements in RFD and EMG amplitude (particularly at the onset of contraction) following resistance training.(Aagaard et al., 2002a, Barry et al., 2005,

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Del Balso and Cafarelli, 2007, Tillin and Folland, 2014, Tillin et al., 2012, Van Cutsem et al., 1998)  Indirect evidence for neural mechanisms contributing to rapid development of contractile force is provided by the increases in voluntary RFD of the untrained limb following unilateral strength and power training.(Adamson et al., 2008)

Skeletal muscle force is increased by activation of additional motor units (recruitment) or more rapid discharge of action potentials (rate coding).  During a voluntary contraction, additional motor units are recruited according to the Henneman size principle, with small, slow oxidative motor units activated first.(Henneman, 1957)  This recruitment order is not affected by the attempted speed of contraction.(Duchateau and Enoka, 2011)  However, rapid voluntary efforts are associated with a high initial discharge rate coupled with doublet discharges.(Desmedt and Godaux, 1977, Van Cutsem et al., 1998)  Discharge rates of > 100 Hz have been recorded during rapid voluntary contractions (Desmedt and Godaux, 1977, Desmedt and Godaux, 1978, Van Cutsem and Duchateau, 2005), compared to rates of 20-50 Hz during slow ramp contractions.(Enoka and Fuglevand, 2001)  Following a period of ballistic training, increase in dorsiflexion RFD was concluded to be primarily due to increase in motor unit discharge rate of the tibialis anterior, with no changes in motor unit recruitment order.(Van Cutsem et al., 1998)

In an exploration of spinal and supraspinal contributors to rapid force development, Johnson et al. concluded that supraspinal neural drive, quantified by Vwave to Mmax ratio, was a strong predictor of ankle plantarflexor rate of torque development (RTD) for all time intervals.(Johnson et al., 2014)  Recurrent inhibition explained less of the variance in RTD than neural drive, but was a significant predictor of RTD.  Postsynaptic inhibition explained a greater percentage of the variance in RTD at earlier time periods (0-50 ms) than later time periods (0-

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200 ms). Greater recurrent inhibition could limit RTD through decreased motor unit discharge rate and potentially, synchronized motor unit discharges.(Del Santo et al., 2007)

Motor unit synchronization has been postulated as a potential neuromuscular mechanism that may influence RFD.(Semmler, 2002) Correlation between discharge times of different motor units would indicate synchronized firing that would, theoretically, improve the ability to rapidly develop contractile force. However, recent investigations indicate that gains in voluntary muscle force production are not associated with changes in motor unit synchronization (Kidgell et al., 2006), and the functional utility of motor unit synchronization has been questioned.(De Luca et al., 1993, Farina and Negro, 2015) Further research is necessary to determine if greater synchronization of motor unit discharges can influence the ability to rapidly develop force.

Fatigue has a more pronounced effect on RFD than maximal strength, particularly early phase RFD (0-50 ms) (Buckthorpe et al., 2014), which could result in diminished performance (e.g. decreased acceleration) or greater risk of injury (e.g. inability to prevent a fall). In agreement with evidence indicating that the initial period of rapid force production is controlled by agonist neural drive, diminished RFD following fatiguing exercise is associated with decreased rate of EMG rise.(Farup et al., 2015)

In summary, there are a variety of supraspinal and spinal mechanisms that can contribute to the ability to rapidly generate contractile force. Further research is necessary to determine the specific mechanisms that mediate the rise in contractile force throughout a rapid voluntary effort, and how these factors are influenced by training, injury, and fatigue.

### Muscle-Tendon factors affecting RFD/Power

A number of muscle architectural factors can influence the ability to rapidly produce force by having an effect on the transfer of tension from muscle to bone. Intrinsic muscle contractile properties dictate the capacity for RFD. The cross bridge cycling rate is considered

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the primary limitation to maximizing rapid force development of the muscle fiber.(Fitts et al., 1991) Thus, larger percentages of type II myosin heavy chain isoforms enlarges the capacity to rapidly generate contractile force.(Harridge et al., 1996) Power athletes or athletes who frequently perform short term high energy movements and would be expected to have a larger proportion of type II muscle fibers have greater normalized RFD than endurance athletes.(Tillin et al., 2010) In addition, a decreased relative proportion of type IIx muscle fibers following a resistance training program was associated with decreased RFD.(Andersen et al., 2010) Increased intracellular calcium concentrations or calcium release could facilitate improved excitation-contraction coupling and may result in faster force development.(Maffiuletti and Martin, 2001) Muscle architecture may also contribute to RFD. Blazevich et al. have suggested that series elastic components can have a significant effect on early phase RFD, with greater fascicle length resulting in greater possible RFD through increased maximal shortening velocity.(Blazevich et al., 2009) Pennation angle could influence RFD in a similar manner.(Earp et al., 2011)

Voluntary RFD can be influenced by tendon viscoelastic properties. Theoretically, a stiffer tendon would allow for more rapid transmission of contractile force to bone.(Kubo et al., 2001, Reeves et al., 2003) Bojsen-Moller and colleagues reported that tendon mechanical properties could account for up to 30% of the variance in knee extensor RFD and also found positive correlations between tendon stiffness and vertical jump performance.(Bojsen-Moller et al., 2005) In addition, Wang et al. noted significant correlations between normalized RFD and tendon stiffness in subjects with achilles tendinopathy.(Wang et al., 2012) Conversely, Hannah et al. concluded that, when isolated from the influence of maximal strength and computed similarly to RFD, tendon stiffness had no relationship to voluntary knee extension RFD.(Hannah

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and Folland, 2015) Previous investigations reporting associations between tendon stiffness and RFD did not consider the potential interplay between muscle-tendon unit stiffness, peak strength, and RFD.

When high intensity electrical stimulation is applied to a muscle, contractile RFD is greater than that produced by a voluntary effort.(Buckthorpe et al., 2012, de Ruiter et al., 2010, de Ruiter et al., 2007) The ratio of voluntary to evoked maximal RFD is typically in the range of 30-50% (Buckthorpe et al., 2012, Cobian et al., 2015b, de Ruiter et al., 2007), which implies that the intrinsic contractile performance of a muscle may not be a limiting factor of voluntary RFD. Through other neuromuscular factors, the system may be unable to fully utilize the rapid force development capacity of the contractile tissue.

In summary, muscle architectural factors can influence the ability to perform rapid joint/segment movements, though more research is required to determine the relative contribution of each of these factors and how relationships vary based on the specific muscle and movement under evaluation.

## Testing and Measurement

### **Power**

Power is the rate at which work is performed. A power calculation requires a change in displacement and thus, power and RFD are not equivalent. Though, expectedly, the ability to rapidly develop force is positively correlated to the ability to produce power.(Haff et al., 2005) Similarly, the ability to express maximal power is an important concept for functional performance. Power is a key factor in the ability to complete specific activities in which a threshold level of force must be reached in a limited amount of time.(Puthoff et al., 2008, Puthoff and Nielsen, 2007) Elite athletes can be differentiated by their ability to generate high power

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outputs.(Baker, 2002, Cronin and Hansen, 2005, Hansen et al., 2011, Lorenz et al., 2013) Adequate muscle power can be a crucial issue for elderly populations in successful performance of daily activities and maintaining safety in ambulation.(Reid and Fielding, 2012) The inverse relationship between the force a muscle can produce and the velocity at which it contracts results in peak power which occurs at submaximal levels of both force and velocity. Thus, peak power can be increased by improving the ability to generate peak force (strength training), or the ability to rapidly contract muscle at low loads (power training).(Haff, 2012) A mixed resistance training approach can increase power throughout the force/velocity spectrum.(Cormie et al., 2011)

Tests of muscle power involve dynamic movements that can be single or multi-joint, open or closed chain.(Neeter et al., 2006) Free weights and machines using weight stacks can be used to measure power or perform power training exercises (Kyrolainen et al., 2005), but pneumatic resistance devices may be most appropriate (Napoli et al., 2014) due to the ability to provide a more constant resistance throughout the contraction which allows for greater movement velocities.(Frost et al., 2008) Surrogate measurements of power have been developed that don’t require expensive equipment or significant time for analysis and are appropriate for clinical use.(Bean et al., 2007, Kockum and Heijne, 2015, Negrete et al., 2010)

Peak muscle power is often measured during multi-joint movements (e.g. leg press, squats) that have some similarities to typical movement patterns during common functional activities (such as rising from a chair, negotiating stairs, lifting objects overhead, etc.). Though contractile RFD is related to the ability to maximize muscle power, a single joint open chain isometric contraction and a multi-joint closed chain effort are clearly different physiological tasks. Similar to peak strength, the time to develop peak power may be 200-300 ms from the

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onset of contraction. As previously noted, this is longer than the time which muscle force develops during most daily and sports activities.(Aagaard et al., 2002a) Thus, despite the movement pattern similarities between tests of closed chain power and common activities, peak power may have limited utility as a predictor of function. Conversely, measurements such as peak acceleration or the contractile impulse beginning from the initiation of contraction may be better predictors of function.(Aagaard et al., 2002a, Knudson, 2009)

### *Power Analysis*

Muscle power is typically measured as the average or peak power attained in a voluntary effort.(Puthoff et al., 2008) Peak power is maximal product of force and velocity, and is typically thought to occur around 30% of peak force, though some studies report peak power development at 60-70% of peak force.(Cronin et al., 2001, Cuoco et al., 2004, Macaluso and De Vito, 2004) The resistance that peak power occurs at will vary by individual, muscle group, and mode of exercise from which power is calculated.

Peak acceleration, which occurs prior to the development of peak power for a given movement, may be a more appropriate analogue for RFD calculations. Muscle power is typically normalized to body weight or peak strength to allow for comparisons between subjects of differing physical abilities. Acceleration, based on its relationship to the force or resistance used (Force = mass * acceleration), should be normalized to the resistance or load in addition to body weight.

## **RFD**

The rate of force development is a measure of the maximum rate of tension development during an isometric contraction.(Wilkie, 1949) This parameter can be utilized to quantify the ability of the neuromuscular system to perform rapid or ballistic muscle actions.(Aagaard et al., 2002a) RFD is calculated through various interpretations of the slope of the force/time

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curve.(Aagaard et al., 2002a, Buller and Lewis, 1965, de Ruiter et al., 2004a) Electrical stimulation delivered with supramaximal current, pulse trains, and high pulse frequencies provides a valid and reliable measurement of the maximum contractile speed properties of the muscle.(de Haan, 1998, de Ruiter et al., 1999, Deutekom et al., 2000) Normalizing voluntary RFD to evoked RFD can provide an indirect measurement of agonist neural drive.

### *Testing and Methodological Considerations*

The gold standard methodology for assessing RFD is to measure the rate of force rise during an isometric contraction executed with the intent of reaching maximum force production as quickly as possible.(Desmedt and Godaux, 1977) Various testing equipment has been utilized in studies of RFD. The necessary equipment can vary considerably based on the joint/muscles being evaluated, subject size and desired positioning, and the available resources. Many investigators have utilized custom built devices consisting of a rigid scaffolding or dynamometer that incorporated a piece of equipment capable of isometric testing with minimal compliance.(de Ruiter et al., 2004a)

Minimizing compliance at the juncture of the testing apparatus and the arm or leg of the subject is crucial for obtaining accurate RFD measurements. Investigators utilizing a standard isokinetic dynamometer with a pad attachment should be cognizant that the compliant pad attachment can result in inaccurate RFD measurements, particularly evident in the initial phases of contraction.(Tsaopoulos et al., 2007) Pilot testing in our laboratory indicates that using a standard pad attachment for knee extensor RFD testing with a Humac NORM isokinetic dynamometer (Computer Sports Medicine, Inc., Stoughton, MA) actually results in increased early phase RFD values, due to the shank building momentum moving into the pad before the force measurement registers. As a result, the RFD values from 0-50 ms are elevated compared to a rigid attachment that eliminates pad compliance.

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In addition to the pad attachment, there may also be additional compliance in the lever arm that attaches to the dynamometer. This could also contribute to the amplified early phase RFD measurements observed when using this equipment. As RFD testing grows in popularity, clinicians and scientists using commonly available dynamometer equipment should be aware of the potential inaccuracies introduced with the use of a non-compliant system. If using a standard isokinetic dynamometer, it is recommended that a load cell is used to collect force signals rather than the torque motor of the dynamometer, due to the increased sensitivity afforded by the load cell.(Buckner et al., 2015)

### *Sampling Rate*

Investigations of knee extensor RFD reveal that healthy people reach roughly 75% of peak force within 150 ms from onset of contraction.(Buckthorpe et al., 2012) Time to maximal RFD, although variable, is typically 30 – 70 ms from onset of contraction.(de Ruiter et al., 2010, de Ruiter et al., 2004a, de Ruiter et al., 2007) Due to the very short time window in which these changes in force are occurring, it is recommended that force signals are sampled at ≥ 2,000 Hz.(de Ruiter et al., 2007, Folland et al., 2014) Similarly, it is recommended that surface EMG collected during RFD contractions be sampled at ≥ 2,000 Hz (Buckthorpe et al., 2012), roughly 4x the presumed maximal frequency of the signal. This satisfies the Nyquist theorem (Clancy et al., 2002) without unnecessary oversampling.(Durkin and Callaghan, 2005)

### *Identification of Signal Onset*

Many characterizations of the RFD signal are based on the onset of contraction (force/torque) or the onset of muscle activation (EMG). As such, valid identification of the signal onset is crucial if data analysis involves measurements such as torque time integrals, or the RFD from onset to a specific endpoint. Manual or visual identification of the signal onset has been purported to be the "gold standard" method.(Tillin et al., 2010) Visual identification is

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typically used as the validation method for forms of automated onset detection.(Di Fabio, 1987, Soda et al., 2010) Automatic detection methods have significant potential to produce noticeable latencies in the identification of signal onset.

Typically, automated methods of signal onset detection are based on arbitrary baseline values (Thompson et al., 2012) or on reaching a percentage of the peak signal value.(Aagaard et al., 2002a, Andersen and Aagaard, 2006, de Ruiter et al., 2004a) Other potential criteria are based on the variability of the baseline signal (Uliam Kuriki et al., 2011) or calculating the derivative of the signal and defining onset as the zero-crossing point.(de Ruiter et al., 2007, Soda et al., 2010) More advanced algorithms have also been employed.(Di Fabio, 1987, Staude and Wolf, 1999)

Determining the point at which the signal truly deflects from the baseline noise is difficult if the signal has been filtered or smoothed. Minimal filtering and smoothing of the raw signal is encouraged to improve accuracy of signal onset detection.(Tillin et al., 2013)

Automated detection methods that consider the baseline variability in the signal and aim to identify the point at which the signal truly deflects from baseline (rather than using an arbitrary criteria for all trials) may provide more efficient data processing and should be explored. Any automated detection methods should utilize algorithms which do not smooth or eliminate the initial toe region of the rising signal (which may be the most important in terms of performance or injury prevention and must be preserved in the data) and should be validated against the results of manual detection of signal onset.

Data should be inspected and repetitions which involve a countermovement prior to force rise be excluded, if attempting to obtain a consistent and valid measurement of RFD from rest, as a countermovement may artificially inflate measured RFD. Rapid voluntary efforts that are

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superimposed on a sustained contraction result in RFD that is both lower in magnitude and less reliable than a rapid effort from rest.(Van Cutsem and Duchateau, 2005)

### *RFD Variables / Interpretations of the Force/Time curve*

RFD is not represented by a single distinct variable. There are a variety of characterizations of the force/time curve that can be identified as RFD variables. Evaluating the peak slope of the rise in force provides a measurement of the maximal capability of neuromuscular system to develop contractile force rapidly. Maximum rate of force development (MRFD) is typically defined as the greatest positive slope (Nm/s) of the force signal (occasionally reported as the average of 3-5 data points), and is the most common and simplistic RFD measurement.(de Ruiter et al., 2004a)

Alternatively, calculating the rise in force from the initiation of contraction to a specified time or force level characterizes the ability to “turn on” the system.(Andersen and Aagaard, 2006, Andersen et al., 2010) Force time integrals (the contractile impulse) from onset of contraction to a specified interval include the time history of the contraction and may have the most functional relevance.(Aagaard et al., 2002c) For movement along a single axis at a joint, Newton’s second law dictates that the contractile impulse is directly proportional to the angular velocity the segment would reach if not restricted by the testing apparatus.(Knudson, 2009) Thus, time integrals may be a meaningful variable in terms of predicting athletic ability such as jump height (de Ruiter et al., 2006) or agility performance.

Normalizing RFD to peak strength measurements allows for analysis of the ability to rapidly increase contractile tension independently of the maximum force producing capability of the muscle. Percentages of peak force reached at specific intervals (e.g. % of peak force at 50 ms from onset of contraction), provide normalized measures of rapid force production, which

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determine speed properties of the neuromuscular system independently of maximal force production capacity, and allow for comparison between subjects of varying strength. It may be most appropriate to consider RFD in successive time windows (e.g. 0-50 ms, 50-100 ms, etc.) as the determinants of RFD may vary throughout the period of contraction, and may have different functional implications.(Folland et al., 2014, Tillin et al., 2010) Agonist neural drive is a strong predictor of RFD throughout the contraction period, but particularly of early phase RFD (0-50 ms).(de Ruiter et al., 2004a, Folland et al., 2014) Intrinsic contractile properties as assessed by evoked twitch contractions are also correlated with early phase voluntary RFD.(Andersen and Aagaard, 2006, Folland et al., 2014) The strongest predictor of late phase RFD (> 100 ms) is maximal voluntary force production.(Andersen and Aagaard, 2006, Folland et al., 2014) Removing both the toe region at the initiation of contraction and the gradual rise to peak force production at the end of contraction and calculating the slope of the force signal in the middle range of the force/time curve (for example, 20% of the peak force to 80% of the peak force) may provide the RFD measurement most representative of the speed properties of the muscle.(Dudley-Javoroski et al., 2008, Folland et al., 2014)

Calculating and/or reporting only a single RFD variable may not be sufficient due to the factors discussed in the preceding paragraph. The specific variables used to characterize RFD should be dependent on the purpose of the investigation, the equipment utilized for collection, and the data obtained. By utilizing multiple characterizations of the rate in rise, the neuromuscular determinants of the changes, differences, or limitations in voluntary RFD can be explored. This information has relevance for designing interventions to properly target the neuromuscular system to obtain the desired outcomes.

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### *Electrically Evoked RFD*

Electrically stimulated contractions produce greater absolute RFD values than voluntary contractions (Buckthorpe et al., 2012, de Ruiter et al., 2010, de Ruiter et al., 2007), which indicates that the muscle itself is capable of a more rapid increase in force production, but may be limited by central mechanisms of neuromuscular activation in a typical voluntary effort. In a recent investigation, Tillin et al. found that power athletes had similar evoked RFD values to untrained individuals. However, athletes recorded greater voluntary RFD, and this discrepancy was nearly entirely accounted for by differences in neural activation.(Tillin et al., 2010) Unsurprisingly, the reliability of electrically evoked RFD is greater than voluntary RFD.(Jenkins et al., 2013)

### *Stim parameters to maximize RFD*

It has been suggested that an 8-pulse, 300 Hz train (100 µsec pulse duration) is required to induce the maximum quadriceps muscle contractile speed properties (de Ruiter et al., 2004a), and this remains the current standard for investigations of RFD in humans.(Folland et al., 2014) However, these recommendations are largely based on studies which evaluated neuromuscular performance in animals (Buller and Lewis, 1965, de Haan, 1998), investigations which have not been repeated in humans. Due to the discomfort associated with high intensity octet stimulation (Tillin et al., 2012), it would be beneficial to determine if there is an optimal pulse sequence to induce maximal RFD while minimizing subject discomfort. Muscle specific stimulation parameters should also be investigated.

Pilot work performed in our laboratory indicates that a 100 µs, 100 Hz triplet is about 25% more comfortable than an octet and produces absolute quadriceps MRFD values of roughly 10% less than those produced by octet stimulation. When normalized to peak evoked force, triplet and octet stimulation produce similar MRFD.

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*Variability of RFD*

It is important to recognize that force and EMG signals obtained from rapid voluntary efforts have significantly greater within-subjects variability than signals produced during slow ramp contractions.(Buckthorpe et al., 2012, Clark et al., 2007, Jenkins et al., 2013) Generally, as the time interval shortens, we can expect increased variability. Sample sizes must be appreciably larger in order to reach statistical significance when testing short interval RFD measurements. Due to the greater variability of RFD trials, RFD calculated as the average of 3-5 trials, or the best 3 of 5 efforts, is recommended rather than recording the maximum value from a single trial.(Tillin et al., 2011, Tillin et al., 2012)

*Subject Considerations - Instruction, Motivation, Feedback, Familiarity*

It is very important that subjects understand the goal of the task and are provided with proper and complete instruction regarding the desired effort. Previous investigations (Holtermann et al., 2007b, Sahaly et al., 2001) indicate that emphasis on the word “fast” results in significantly greater voluntary RFD. If trials to assess peak force production (typically referred to as maximal voluntary isometric contractions – MVICs) are also being performed, a clear distinction should be made between ramp MVIC and RFD trials. Figure 1.1 illustrates the overall profiles of MVIC and RFD trials performed by the same subject. To perform the ramp MVIC trial, the subject was instructed to kick out “as hard as possible” until instructed to relax. To perform the RFD trial, the subject was instructed to kick out “as fast and as hard as possible”, with emphasis on the word fast. It is obvious the slope of the force rise in the RFD trial is significantly different than the MVIC trial, which cannot be used to properly evaluate voluntary RFD.

Multiple investigations have been published in which the RFD of a ramp MVIC contraction was evaluated (Carcia et al., 2012, Kline et al., 2015, Winters et al., 2013), or in

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which the subject was not instructed to perform the voluntary effort with an emphasis on fast/rapid movement.(Hsieh et al., 2014) This is not a valid measure of voluntary RFD as the subjects in these studies were not instructed to attempt to perform the contraction with any type of emphasis on a rapid contraction. As RFD becomes a more popular topic in the fields of performance enhancement and rehabilitation, researchers and editors should be aware of the insignificance of attempting to evaluate the RFD of a ramp contraction or an effort in which the subject was not properly instructed to produce force as rapidly as possible.

To evaluate the maximal RFD of the neuromuscular system, it is recommended that subjects be instructed to perform the contraction both rapidly and with maximal effort. If a subject performs the effort quickly but without maximal effort, later phase RFD variables are likely to portray the ability to rapidly develop force inaccurately. Thus, it is recommended that a target peak force is provided for the subject to reach (if visual feedback is available), or trials should be inspected in real time to ensure that peak torque is reaching near-maximal MVIC values (often, 80% is used as a goal).(Buckthorpe et al., 2012)

Similar to other tasks requiring maximal voluntary effort, subjects need to be properly motivated to produce RFD to the best of their abilities. Verbal encouragement (McNair et al., 1996) and visual feedback of results (Figoni and Morris, 1984) are recommended to maximize force production. However, these suggestions are based on tests of maximal force production, not rapid force production as these concepts have yet to be thoroughly investigated in regards to RFD. The very short time window during which the rapid force production is performed likely renders real-time feedback meaningless, but subjects most likely benefit from feedback of results.

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Rapid isometric force production is a novel task for the vast majority of subjects. Practice trials are required and should be completed until subjects can perform the rapid voluntary force production task confidently and consistently with maximal effort. Pilot testing in our laboratory indicates subjects should perform a minimum of 5-10 submaximal rapidly voluntary efforts prior to performing a test/recorded trial.

## Response to Training

### Power Training

Power training has been shown to be effective in improving functional outcomes, as well as lower extremity strength and power, in elderly individuals.(Fielding et al., 2002, Sayers and Gibson, 2012, Sayers et al., 2012) Power training in athletic populations has also been demonstrated to improve jump height and endurance performance.(Cormie et al., 2011, Paavolainen et al., 1999) Training with both low and high loads can improve power production, though there are typically greater improvements in strength with high load training.(de Vos et al., 2005, Orr et al., 2006) More important than the external resistance is the intent to move the load as quickly as possible.(Fielding et al., 2002, W.B. and G.E., 1993) Neuromuscular adaptations are specific to the training stimulus, and without the intent to move quickly, power may increase minimally (due to changes in peak force production) or decrease (due to decreases in velocity). The ideal training load can vary considerably based on the individual, the movement being performed, the equipment used, and how power is calculated.(Harris et al., 2007)

### RFD Training

Training with rapid force development results in distinct adaptations of the neuromuscular system that are specific to the training stimulus.(Tillin and Folland, 2014, Tillin et al., 2012, Williams, 2011) Training with explosive isometric efforts induces a velocity-specific

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response, indicating that it is the intent of the movement, rather than the actual speed of movement, which causes the training response.(Behm and Sale, 1993) Improvements in early phase neuromuscular activation are associated with gains in RFD following rapid isometric training.(Tillin and Folland, 2014) In addition, maximal voluntary isometric contractions executed with rapid rise in force can produce similar gains in peak strength as slower ramp contractions.(Maffiuletti and Martin, 2001, Williams, 2011)

### Special Populations

### Elderly

A combination of reduced activity levels and age associated changes in the neuromuscular system translates to declining muscle performance with increasing age. Due to the nature of these changes, muscle power and RFD decline at a faster rate than peak muscle strength. Changes related to power/RFD include a loss in muscle mass, preferential loss and/or atrophy of Type II muscle fibers, slower neural conduction velocity, decreased tendon stiffness, and increased antagonist co-activation.(Davies and White, 1983, Lexell et al., 1988, Macaluso and De Vito, 2004, Macaluso et al., 2002, Sato et al., 1984) As discussed in this review, each of these factors could negatively affect RFD or power.

Power is an important concept for elderly populations in maximizing daily function and maintaining safety in movement.(Reid and Fielding, 2012) In elderly individuals, muscle power has been shown to be more strongly related to measures of function than peak muscle strength. Power is related to walking speed and distance, stair climbing ability, sit-to-stand performance, Short Physical Performance Battery score, and falling/loss of balance.(Allen et al., 2010, Bento et al., 2010, Brach et al., 2001, Clark et al., 2013, Clark et al., 2011, Holsgaard-Larsen et al., 2011, Larsen et al., 2009, Puthoff et al., 2008, Puthoff and Nielsen, 2007) As a combination of

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force and speed, the power or RFD variables that demonstrated the closest relationships to these activities depends on the requirements of the activity.

### *Power training in the elderly*

Due to the loss of muscle power and the ability to rapidly produce force associated with aging (and the functional consequences of these changes), numerous investigations have evaluated the response to power training in elderly populations. Training with a focus on rapid action or attempting to move a load as quickly as possible has been shown to improve muscle power and functional performance in older adults.(Caserotti et al., 2008, Earles et al., 2001, Fielding et al., 2002, Sayers and Gibson, 2012, Sayers et al., 2012) Tschopp published a recent meta-analysis which concluded that power training may provide additional benefits beyond what can be gained from a strength training program.(Tschopp et al., 2011) Other investigations have reported greater gains in balance, Continuous Scale Physical Functional Performance, stair climbing and sit-to-stand performance with power training when compared to traditional/slower speed strength training.(Bottaro et al., 2007, Miszko et al., 2003, Orr et al., 2006)

## **Athletes**

### *Potential Functional Importance of Power/RFD*

For athletes, the ability to rapidly develop high levels of muscle force can be extremely important to optimal performance of sport related tasks such as rapidly changing direction, accelerating, maximizing jump height, and reacting to external stimuli.(de Ruiter et al., 2006, Spiteri et al., 2015) A large percentage of sports-related tasks are time limited and require a rapid response for successful performance, such as hitting a 95 mph fastball or cutting to the basket to receive a pass, planting and turning slightly to avoid a defender. All of these actions, from the impulse to the outcome, must occur in very short periods of time. Elite athletes in fast twitch sports are defined by their abilities to rapidly respond to stimuli, generate high muscle

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power, and accelerate/decelerate as quickly as possible.(Lorenz et al., 2013) People who can rapidly activate muscle and rapidly develop contractile force at rates greater than their competitors will be more successful in accomplishing sports-specific tasks.

#### *Relationships between Power/RFD and performance*

Previous investigations indicate strong relationships between muscle power and athletic performance. A defining characteristic of elite athletes is their ability to generate high relative values of peak muscle power rapidly. Jump performance has been shown to be related to knee extensor and ankle plantarflexor RFD.(Chang et al., 2014, de Ruiter et al., 2006) Agility and other sports performance criteria are also related to the ability to rapidly generate force.(Beretic et al., 2013, Spiteri et al., 2015, Stone et al., 2004, West et al., 2011)

### People who have sustained injury and/or surgery

The effect of trauma or surgery on the ability to rapidly activate skeletal muscle and develop contractile force is not well defined. There is some evidence that knee injury may result in greater limitations in rapid force development than peak strength (Angelozzi et al., 2012, Knezevic et al., 2014), and that RFD may be a meaningful marker of recovery in relation to function.(Maffiuletti et al., 2010) People undergoing unilateral total knee arthroplasty present with diminished ability to rapidly produce knee extensor force in their involved limbs both prior to and after surgery. In these patients, side to side deficits in RFD were greater than deficits in maximum strength.(Gapeyeva et al., 2007) In addition, there was a stronger relationship between RFD and patient-based outcomes scores and knee pain than peak strength and pain or outcomes.(Maffiuletti et al., 2010) Angelozzi et al. recently investigated peak strength and RFD with an isometric leg press in 45 professional soccer players who sustained ACL rupture and underwent reconstruction. At 6 months post-surgery, peak strength of the involved limb was

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97% of the pre-injury value while RFD was between 63% and 80% of the pre-injury value.(Angelozzi et al., 2012)

### *Potential Functional Importance of Power/RFD*

Similarly to what has been demonstrated in elderly adults and athletes, the ability to rapidly develop force or maximize muscle power can have notable functional consequences in people recovering from injury and surgery. In the context of knee injury, quadriceps neuromuscular dysfunction is commonplace (Drechsler et al., 2006, Ingersoll et al., 2008, Williams et al., 2005a) and would be expected to negatively affect power and RFD. Peer reviewed articles available at this time indicate a relationship between power/RFD and patient-based outcomes that may be stronger than the relationship between peak strength and function.(Cobian et al., 2015b, Hsieh et al., 2014, Maffiuletti et al., 2010) This is a logical outcome when considering the ways in which humans activate muscles and produce muscle force to perform typical daily (or sports) activities, which rarely require peak force production.

No singular measure of power or RFD has been shown to be the most important in terms of predicting function, sports performance, or quality of life.(Cronin and Sleivert, 2005) Although there is evidence that power and function are more strongly related than strength and function, the results of investigations comparing power and function also demonstrate variable results. More research is necessary to truly understand how rapid muscle activation and/or muscle power specifically contributes to successful performance of movement strategies or tasks required in sports or everyday life.

### *Rehabilitation Practices in Relation to RFD/Power*

Typical rehabilitation strategies following injury/surgery begin with low level sustained contractions with gradual onset of muscle contraction and gradual relaxation. In addition, people are more sedentary after injury and likely to attempt to protect the injured limb by avoiding

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higher intensity muscle contractions. As the injury and/or surgery itself causes notable neuromuscular dysfunction, training with low intensity, low speed, and limiting typical functional movements may contribute to additional slowing of contraction velocity and thus, further inhibit function. Exercise interventions to improve power or rapid movements aren't performed until weeks or months into the rehabilitation process (depending on the extent of the impairment). The etiology for this approach is to avoid interventions that could risk compromise of surgical repair or exacerbate post-injury/surgical inflammation. However, when prescribed with proper recognition of the injury and dosed appropriately, high intensity training can result in significantly greater muscle performance and functional gains (Bade and Stevens-Lapsley, 2011, Gerber et al., 2007) and may result in earlier normalization of function. Ultimately, this could contribute to better movement biomechanics, and improve both short term performance and long term quality of life.

Clinicians must be cognizant of the limitations in the patient population and the need to avoid deleterious stresses following injury or surgery, but treating with the current strategies results in sustained deficits in muscle performance and movement biomechanics.(Hall et al., 2012, Noehren et al., 2013, Thomee et al., 2012) Not too long ago patients were often immobilized following typical surgical procedures as a means of protection and to allow for healing. For many orthopaedic conditions, that is no longer common practice as it was shown to substantially limit recovery. Although we have progressed in our understanding of how the body responds to trauma and adapts to rehabilitation intervention, we have a long way to go in terms of being more aware of how people use their muscles to accomplish typical activities and appropriately training to maximize performance.

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By more specifically evaluating the neuromuscular response to knee injury and surgery in regards to RFD, investigating the cause of these limitations, and exploring the value of these measurements in regards to function, we can determine if these concepts should become a component of typical evaluation and treatment.

## Purpose and Specific Aims

This series of studies aims to assist in filling gaps in the knowledge base by characterizing the deficits in quadriceps function related to rapid muscle activation and force production. The ultimate goal of this work is to improve the treatment and rehabilitation of people suffering from knee injury and surgery to facilitate better outcomes and long term quality of life.

It is unclear what effect knee injury or surgery has on the neuromuscular system's ability to rapidly generate force, the mechanisms responsible for these changes, and the relationships between explosive muscle action, movement biomechanics and overall function. Quadriceps muscle atrophy, weakness, and inhibition are present following arthroscopic knee surgery.(Ingersoll et al., 2008, McLeod et al., 2012, Palmieri-Smith et al., 2008) Objective measurements of quadriceps function largely focus on peak strength.(Hartigan et al., 2010) But many activities of daily living and most athletic movements require rapid force development, not maximal force development. Recent investigations suggest that functional ability (Clark et al., 2011), safety in movement (Bento et al., 2010), and patient-based outcomes (Maffiuletti et al., 2010) are more closely related to rapid force development than they are to peak force. Chapter 2, which is entitled *Knee Extensor Rate of Torque Development after Arthroscopic Partial Meniscectomy*, presents an investigation designed to evaluate knee extensor RTD prior to and in

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the month following arthroscopic meniscal debridement and explore the neuromuscular factors that influence the ability to rapid produce knee extensor torque following injury and surgery. In this study, 20 subjects completed tests of quadriceps muscle performance prior to surgery and at 2 weeks and 5 weeks after surgery with each leg. The testing protocol included voluntary isometric knee extension RTD contractions (kicking out as fast and as hard as possible), evoked contractions, quadriceps strength and activation testing, and patient-based outcomes measures. Based on preliminary data and the results of previous investigations regarding quadriceps performance following knee surgery, the following hypotheses were developed:

**Hypothesis 2.1:** Patients undergoing APM will present with significant side to side asymmetries in the ability to rapidly produce knee extensor torque at 2 and 5 weeks after surgery.

**Hypothesis 2.2:** Patients undergoing APM will present with side to side asymmetries in quadriceps neural activation in the early period of rapid voluntary efforts. The deficits in voluntary neural activation are expected to parallel the deficits in rapid voluntary torque production.

**Hypothesis 2.3:** RTD will be more closely related to subjective knee function than measures of maximal voluntary strength. It is expected that improvements or deficits in the ability to rapidly develop knee extensor torque will be associated with positive or negative changes in self-reported knee function.

Power is the rate at which work is performed. A power calculation requires a change in displacement and thus, power and RFD are not equivalent, though rapid force development and

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power production are positively correlated.(Haff et al., 2005) Power may be an important concept in functional performance.(Puthoff et al., 2008, Puthoff and Nielsen, 2007) In particular, power is an important concept for elderly populations in maximizing function and performing activities of daily living.(Bottaro et al., 2007, Miszko et al., 2003, Orr et al., 2006) Current evidence suggests that muscle power is a more sensitive measure of functional status than muscle strength.(Reid and Fielding, 2012) It is important to understand how injury and/or surgery alters the ability to generate power or rapidly produce muscle force. Chapter 3, *Closed Kinetic Chain Lower Extremity Power and Neuromuscular Performance after Arthroscopic Partial Meniscectomy*, details an investigation designed to evaluate leg press (LP) power and isometric knee extensor rate of torque development (RTD) before and after arthroscopic meniscal debridement and analyze the relationships between open and closed chain measures of strength, power, quadriceps neuromuscular performance, and patient reported outcomes. Subjects completed tests of lower extremity (LE) strength, power, and function prior to surgery and at 2 weeks and 5 weeks post-surgery with each leg. The testing protocol included closed chain strength and power tests using an instrumented pneumatic LP, voluntary isometric rapid knee extension contractions (kicking out as fast and as hard as possible), evoked contractions, strength and activation testing, and patient-based outcomes measures. Based on pilot investigations and review of published literature, the hypotheses of this study were:

**Hypothesis 3.1:** Patients undergoing APM will have significant side to side asymmetries in LP strength, power, acceleration, and knee extensor RTD after surgery.

**Hypothesis 3.2:** LP Power and RTD will be more closely associated with patient reported outcomes than peak strength.

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**Hypothesis 3.3:** Subjects will demonstrate greater side to side asymmetries in knee extensor RTD than in LP Power after APM.

Previous investigations indicate that people have significant deficits in knee extensor RTD and rapid quadriceps muscle activation after knee surgery, and that these deficits are more closely related to subjective knee function than deficits in peak strength.(Cobian et al., 2015b, Maffiuletti et al., 2010) Strengthening exercises following knee injury/surgery typically involve a gradual progression of ramp style moderate intensity muscle contractions.(Wilk et al., 2012) Recent evidence suggests that we should explore methods to safely train with rapid muscle contractions in early rehabilitation.(Cobian et al., 2015b) It is unclear how the rate of training affects RTD, rapid muscle activation, and outcomes following knee surgery. Chapter 4 is entitled *Performing Faster Quadriceps Contractions in Rehabilitation after Arthroscopic Partial Meniscectomy is Associated with Greater Rapid Torque Development Capacity and Better Patient Reported Outcomes*. This chapter presents a study in which the rates of knee extensor torque development and quadriceps activation during quadriceps rehabilitation after APM were explored in regards to changes in quadriceps RTD, rapid muscle activation, and patient-based outcomes. 15 subjects completed tests of quadriceps speed, strength, and function prior to and at 2 weeks and 5 weeks after APM. Voluntary isometric knee extension RTD contractions (kicking out as fast and as hard as possible), MRI evaluation of quadriceps muscle volume, and patient-based outcomes measures were completed at each interval. Following surgery, subjects completed 10 high intensity isometric knee extension training sessions (2-3x/week). Torque production and quadriceps surface electromyography (EMG) were collected during training.

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Training data was analyzed to determine training intensity, RTD throughout the training period, and rate of EMG rise during knee extension efforts.

The hypotheses related to this investigation were as follows:

**Hypothesis 4.1:** Patients who trained with faster knee extensor rate of torque development (RTD) following APM would be able to produce greater maximal RTD at the post-training test session.

**Hypothesis 4.2:** Patients who trained with faster knee extensor RTD following APM would have better patient-based outcomes scores following training.

**Hypothesis 4.3:** Changes in quadriceps muscle strength and volume would be associated with normalized torque integrals (training intensity) but not with training RTD following APM.

Quadriceps muscle atrophy, weakness, activation failure, and diminished control of movement are nearly universal after ACL injury.(Ingersoll et al., 2008) Rehabilitation following ACL injury and reconstruction typically focuses on restoring quadriceps strength and activation.(Palmieri-Smith et al., 2008) Objective measurements are largely focused on peak strength. But, typical activities of daily living, such as ascending stairs (Holsgaard-Larsen et al., 2011), rising from a chair (Brach et al., 2001), and most sports activities (de Ruiter et al., 2006, Spiteri et al., 2015) require rapid force development, not maximal force development. It's rare that people, including athletes, actually produce maximal force. There is a gap in the literature regarding the impact of ACL injury on rate of force development and how rate of force development / power may influence knee biomechanics and a patient's functional outcomes.

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Chapter 5, which is entitled *Lower Extremity Power and Knee Extensor Rapid Force Development after Anterior Cruciate Ligament Reconstruction*, describes a proposed investigation of rapid lower extremity force development and lower extremity power at a clinically important time period after ACL reconstruction. The objective of this investigation is to characterize the deficits in rapid lower extremity force development after ACL reconstruction, and determine if and how the ability to rapidly develop force and generate power is related to movement biomechanics, common clinical tests of leg function, and knee-related quality of life. Subjects less than one year post-ACL reconstruction performed isometric quadriceps strength and activation testing, hop tests, tests of rapid force development, and completed evaluation of movement biomechanics when walking over level ground and stepping down from curb height. Subjects also completed patient-rated outcome measures of knee function. The central hypothesis of this proposal was that measures of rapid quadriceps force development are more sensitive than measures of peak strength after ACL injury, are limited by central mechanisms, and are more strongly associated with knee function and lower extremity biomechanics. The following detailed hypotheses were postulated based on the results of previous investigations, pilot data of individuals with previous ACL reconstruction, and current literature/understanding of the neuromuscular consequences of ACL injury and surgery:

**Hypothesis 5.1:** Subjects will demonstrate significant side to side asymmetries in the ratio of voluntary/evoked quadriceps RFD, quadriceps EMG RMS value from onset of contraction to 50 ms, and quadriceps RFD from onset of contraction to 50 ms. Contractile speed properties (assessed with pulse trains of electrical stimulation) will not be significantly different by limb. There will be no side to side asymmetry in quadriceps

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Voluntary Activation failure (assessed by modified triplet-superimposition method during a maximal voluntary contraction and at rest).

**Hypothesis 5.2:** Peak knee extensor moments and peak knee power absorption during the stance phase of both walking tasks will be more strongly correlated with RFD and LE power than MVIC or leg press 1RM. Single leg hop height and distance will be more strongly correlated with RFD/power than MVIC/1RM. Subjects with greater deficits in the ability to rapidly produce quadriceps force will demonstrate decreased knee flexion range of motion, peak knee extensor moments, and peak knee power absorption of the involved limb during stance phase in both gait tasks.

**Hypothesis 5.3:** Self-reported knee function after ACL injury and reconstruction will be more strongly correlated with RFD and power than MVIC/1RM. Subjects with greater side to side asymmetries in the ability to rapidly produce force will record lower IKDC, KOOS, ACL-RSI, and TSK-11 scores.

## Summary and Significance

Many people who have undergone arthroscopic knee surgery present with chronic abnormal movement biomechanics and quadriceps neuromuscular dysfunction, which increases the risk of recurrent injury or long-term intra-articular degradation. This implies that our rehabilitation strategies following arthroscopic knee procedures are less than optimal and require continued focus. This proposal represents an important first step in research on the importance of rapid force development and muscle power to functional recovery after knee injury and surgery, and lays the groundwork for more comprehensive analysis of the neuromuscular mechanisms responsible for injury-related changes in the ability to rapidly produce force.

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This document presents a unique series of studies designed to improve our understanding of neuromuscular function and the ability to rapid develop muscular force in the context of knee injury and surgery. If warranted, future work may also focus on modifying rehabilitation strategies to improve rapid force development in a safe and effective manner. In the long term, this may prove to be a very important concept in the rehabilitation and treatment of musculoskeletal injury, which could facilitate a shifting in the focus of therapeutic exercise interventions following injury. Patients may be able to safely return to sports and/or typical daily activities sooner, with more normal function for better short term performance and long term joint health. This work has implications for improvements in clinical care and better understanding of the physiological responses to trauma.

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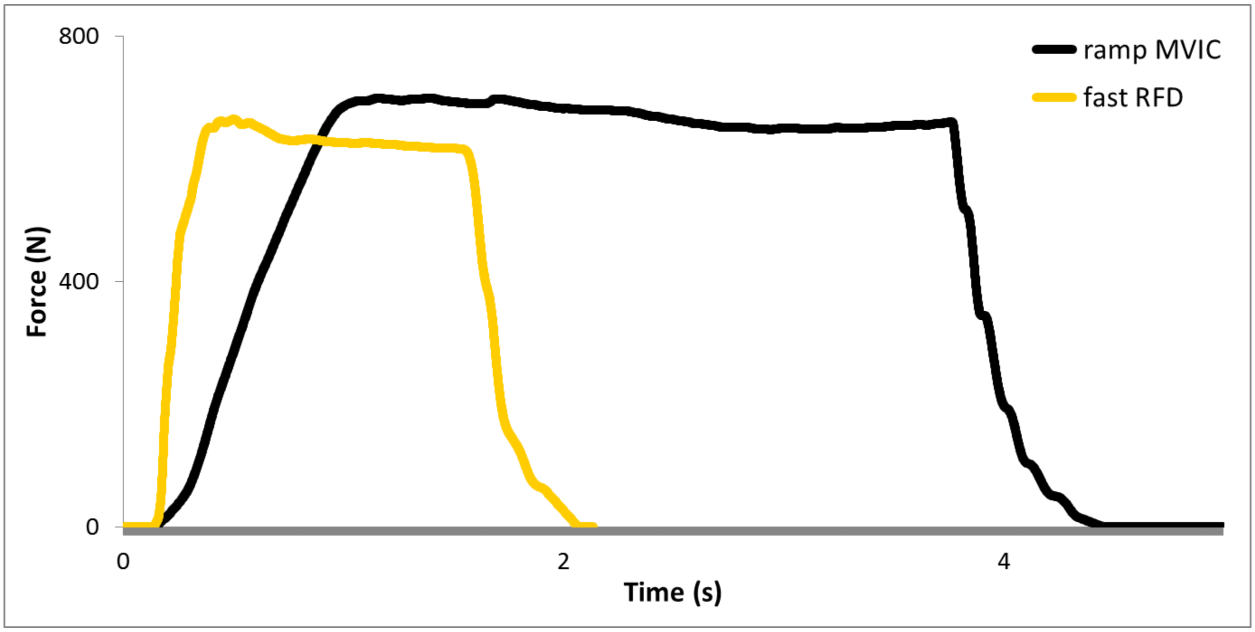

Figure 1.1: Comparison between knee extensor MVIC and RFD trials. Two isometric knee extension force/time signal curves produced by the same subject are depicted. In one trial (ramp MVIC), the subject was instructed to kick “as hard as possible”. In the other (fast RFD), the subject was instructed to kick “as fast and as hard as possible” with emphasis on fast.

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# CHAPTER 2

## KNEE EXTENSOR RATE OF TORQUE DEVELOPMENT AFTER ARTHROSCOPIC PARTIAL MENISCECTOMY

### Introduction

Arthroscopic Partial Meniscectomy (APM) is one of the most common orthopaedic procedures, with nearly 500,000 operations completed annually in the United States.(Kim et al., 2011) The goal of this procedure is to reduce or eliminate symptoms attributed to a torn or compromised meniscus by creating a stable rim. This is a reproducible and minimally invasive procedure and a rapid return to daily, work, and sports activities is typically allowed.(Lubowitz et al., 2008, Umar, 1997) Current standard of practice is to allow patients to resume normal activities without formal post-operative physical therapy.(Goodwin and Morrissey, 2003)

However, research has shown that people undergoing knee arthroscopy to address meniscus lesions present with notable deficits in quadriceps strength and neuromuscular function both prior to(Stensrud et al., 2014) and following surgery(Akima and Furukawa, 2005, Akima et al., 2008, Ericsson et al., 2006, Gapeyeva et al., 2000, Glatthorn et al., 2010, Hall et al., 2013, McLeod et al., 2012, Sturnieks et al., 2008, Suter et al., 1998) that may contribute to abnormal movement biomechanics(Durand et al., 1993, Hall et al., 2013, Moffet et al., 1993) and limit knee-related quality of life.(Roos et al., 2001, Roos et al., 2000) Quadriceps muscle atrophy, weakness, and inhibition are found in both the short(Durand et al., 1993, Suter et al., 1998) and long term(Becker et al., 2004) following APM.

Typically, post-operative quadriceps muscle performance is quantified by measuring peak strength.(Logerstedt et al., 2013, Mizner et al., 2005) However, the speed of typical human movement precludes peak muscle force development during most daily or sports activities.

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Investigations of lower extremity muscle activation patterns during walking, running, and other activities indicate that many common movements are characterized by patterns of rapid muscle activation and relaxation.(Cappellini et al., 2006, Gazendam and Hof, 2007, Rand and Ohtsuki, 2000) Thus, the ability to rapidly activate muscle and/or rapidly develop muscle force may be more important to maintaining or improving function. Research in geriatrics and other populations suggests that functional ability, safety in movement, and patient-based outcomes are more closely related to rate of force development and lower extremity power than they are to peak strength.(Allen et al., 2010, Bento et al., 2010, Clark et al., 2011, Holsgaard-Larsen et al., 2011, Maffiuletti et al., 2010, Puthoff et al., 2008, Puthoff and Nielsen, 2007, Reid and Fielding, 2012)

Recent investigations of patients following anterior cruciate ligament (ACL) reconstruction or total knee arthroplasty (TKA) indicate that deficits in the ability to rapidly develop force are greater than the deficits in peak force(Jordan et al., 2014, Knezevic et al., 2014) and can persist after deficits in peak strength have been resolved.(Angelozzi et al., 2012) The potential relevance of these concepts to knee and lower extremity function suggest that rapid muscle force development may be an important concept to address in both testing and rehabilitation.

The rates of force and torque development (RFD or RTD) are measures of the maximum rate of tension development during an isometric contraction.(Wilkie, 1949) These parameters can be utilized to quantify the ability of the neuromuscular system to rapidly increase muscle force production, and are calculated through various interpretations of the slope of the force/time curve.(Aagaard et al., 2002a, de Ruiter et al., 2004a) When normalized to peak force, RFD has a strong positive relationship with agonist muscle activation, particularly in the very early period

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of force rise.(de Ruiter et al., 2004a, de Ruiter et al., 2006, de Ruiter et al., 2007) Training studies indicate that increased agonist neural drive can result in improved capacity to rapidly develop force.(Aagaard et al., 2002a, Barry et al., 2005, Hakkinen et al., 1985, Tillin and Folland, 2014, Tillin et al., 2012, Van Cutsem et al., 1998) Electrical stimulation with high pulse frequencies and pulse trains has been shown to be effective in evaluating the maximum contractile speed properties of muscle.(de Haan, 1998, Deutekom et al., 2000) Voluntary efforts represent an individual’s ability to utilize the contractile properties of the muscle. Comparing the evoked and voluntary efforts can provide valuable information concerning the neuromuscular determinants of RTD.(de Ruiter et al., 2004a, de Ruiter et al., 2007) To date, there have not been any published reports investigating the neuromuscular factors contributing to rapid quadriceps force development following arthroscopic knee procedures.

The purpose of this investigation was to test the following hypotheses:

1) Patients undergoing APM will present with significant side to side asymmetries in the ability to rapidly produce knee extensor torque at 2 and 5 weeks after surgery.
2) Patients undergoing APM will present with side to side asymmetries in quadriceps neural activation in the early period of rapid voluntary efforts. The deficits in voluntary neural activation are expected to parallel the deficits in rapid voluntary torque production.
3) RTD will be more closely related to subjective knee function than measures of maximal voluntary strength. It is expected that improvements or deficits in the ability to rapidly develop knee extensor torque will be associated with positive or negative changes in self-reported knee function.

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## Methods

### Subjects

20 people undergoing arthroscopic meniscal debridement (10 males, 10 females, mean age 42.3 ± 13.7, mean BMI 26.6 ± 3.1) volunteered to participate in this study. All subjects were right leg dominant as determined by which leg they would choose to kick a ball with. Exclusion criteria included concomitant knee ligament injury, recent lower extremity fracture, BMI > 40, inability to complete an MRI, history of neurological disorder, quadriceps muscle tear, or any other medical condition that created a safety concern or could negatively affect the validity of the results. Potential subjects were asked screening questions and completed a basic lower extremity physical exam. This investigation was approved by the University of Iowa Institutional Review Board, and all subjects provided written informed consent. Subjects in this study were part of a larger randomized controlled trial investigating the effects of various exercise protocols on the quadriceps muscle following APM. Subjects were randomized to one of three treatment groups, and completed 10 rehabilitation sessions following surgery prior to the final (5 week post-surgery) test session.

### Testing Procedures

Subjects completed a battery of tests and measures prior to surgery and approximately 2 weeks and 5 weeks after surgery with each leg. Tests were performed in consistent order at each interval.

### Patient-based Outcomes Measures

Subjects completed the KOOS, WOMET, and UCLA activity score, valid and reliable instruments for evaluating patient-reported outcomes in this population.(Naal et al., 2009, Roos and Lohmander, 2003, Sihvonen et al., 2012)

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### Quadriceps Volume Measurement

A Siemens TIM Trio 3T scanner was utilized to acquire axial T1-weighted images of quadriceps muscles volume (Siemens Medical Solutions USA, Inc., Malvern, PA). The outer borders of the quadriceps muscle group in each axial slice were manually traced using Medical Image Processing, Analysis, and Visualization (MIPAV) software. A single author (C.K.) performed all tracings while blinded to subject identity and group. Muscle volume was calculated using statistical algorithms in MIPAV. The excellent reliability [$ICC_{(2,1)} = 0.98$, $p < .001$] of this technique has been previously established.(Segal et al., 2014)

### Testing of Quadriceps Muscle Contractile Properties, Strength, Activation, and RTD

Evaluation of the uninvolved leg always preceded testing of the involved leg. Contractile properties were completed first, followed by strength/activation, and RTD. Skin preparation was completed and surface EMG electrodes (model 544, Therapeutics Unlimited, Iowa City, IA) were applied over the muscle bellies of the vastus lateralis (VL), rectus femoris (RF), and vastus medialis (VM). Subjects were seated in the chair of an FDA approved Testing & Rehabilitation System (HUMAC NORM, Computer Sports Medicine, Inc., Stoughton, MA) with hip and knee angles of 85 and 90 degrees, respectively. Subjects were secured with Velcro straps across the chest and thighs. The pad of the knee testing adapter was fixed to the shank approximately 5 cm proximal to the medial malleolus. Chair position was adjusted for each individual subject to align the dynamometer center with the knee joint axis of rotation. These custom alignments were saved and utilized at each subsequent data collection (Figure 2.1).

Self-adhesive muscle stimulation electrodes were applied to the subject’s anterior (over the femoral nerve) and lateral (over the greater trochanter) thigh. Electrical stimulation was

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delivered to the quadriceps musculature using an FDA approved constant current stimulator (Digitimer Ltd., Model DS7AH, Hertfordshire, England). Subject-specific stimulus intensity was determined by increasing current (beginning at 50 mA) until force production plateaued (subsequent increases decreased force) while the subject sat at rest. 110% of the intensity required to produce peak twitch torque was selected for use in contractile properties and voluntary activation tests.

While seated at rest, subjects completed a series of electrically evoked doublets. Pulses were delivered in series with 10 seconds of rest between each pulse. Doublet stimulation was delivered with a square wave pulse at 100 Hz with 1 ms pulse duration and 400 V.

After completing warm-up repetitions to become familiarized with the testing conditions, subjects performed at least two maximal voluntary isometric knee extension ramp contractions (MVIC), with 2 minutes rest between efforts, to reliably determine peak knee extensor torque. Subjects were instructed to kick out as hard as possible and loud verbal encouragement was provided to facilitate maximal torque production. These efforts were repeated, with 2 minutes rest, until multiple trials were recorded in which peak torque did not vary by greater than 5%. After peak torque was reliably identified, subjects were instructed in the performance of rapid voluntary isometric contractions. The purpose of these tests was to assess voluntary RTD of the knee extensors. Subjects were specifically instructed to kick out as fast and as hard as possible, in an attempt to reach peak torque as quickly as possible.(Holtermann et al., 2007b, Sahaly et al., 2001, Bemben et al., 1990) Subjects completed at least 3 practice trials followed by 5 recorded trials (each separated by 30 seconds of rest) in which the subject produced a brief (1 to 2 second) maximum voluntary knee extension contraction (Figure 2.2). In order for the trial to be considered valid, peak torque had to reach at least 80% of the isometric peak torque established

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during slow maximal efforts and no countermovement prior to contraction could be detected. Peak knee flexion strength was also assessed with maximal isometric knee flexion contractions, performed after knee extensor RTD testing.

Quadriceps voluntary activation (VA) was assessed using the interpolated twitch technique (ITT).(Krishnan and Williams, 2010) Subjects performed an MVIC during which electrical stimulation was triggered when the torque produced by the subject reached a threshold based on previously established values.(Krishnan et al., 2009) A second stimulus of equal intensity was delivered shortly after the subject returned to rest in order to assess the muscle in its potentiated state. Subjects completed a minimum of two trials with two minutes rest between each trial. VA was calculated after each repetition and could not vary by greater than 5% or additional trials were performed.

### Signal Sampling and Processing

#### *Torque and EMG Signals*

Torque signals were sampled at 2000 Hz with a 16-bit A-to-D PowerLab data acquisition system (Model ML880, ADInstruments, Inc., Colorado Springs, CO). Signals from the HUMAC NORM were converted to torque values using previously validated conversion factors. EMG signals were sampled at 2000 Hz (Model 544, Therapeutics Unlimited, Iowa City, IA) with a cutoff frequency of 20 Hz. Custom software developed in LabChart v 7.3.7 (ADInstruments, Inc., Colorado Springs, CO) was utilized to record and store torque and EMG signals.

#### *RTD from Voluntary and Electrically Elicited Contractions*

Voluntary and electrically evoked RTD torque signals were processed with custom algorithms created using Python programming language (Python Software Foundation, Beaverton, OR). (see Appendix). Maximum rate of torque development (MRTD) was defined

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as the single data point at which the greatest positive slope (Nm/s) of the torque signal occurred. Torque time integrals (TTI), which may be the most meaningful RTD parameter(Aagaard et al., 2002a, Knudson, 2009), were computed, along with the percentages of MVIC reached at specific time points (e.g. $T_{50}$ for % of MVIC at 50 ms from onset of contraction), which provided MVIC normalized measures of rapid torque production. The slope of the torque signal from 20% of the peak torque to 80% of the peak torque ($RTD_{20\text{-}80}$) was also determined, which may be the period of torque rise most representative of the speed properties of the muscle (Figure 2.3).(Dudley-Javoroski et al., 2008)

#### *EMG Signals from Voluntary RTD Contractions*

EMG signals obtained from the VL, RF, and VM during voluntary RTD trials were processed with custom algorithms created using Python programming language (see Appendix). Electromechanical delay (EMD) for each muscle was calculated as the difference in time between onset of torque and EMG signals. Root mean square (RMS) amplitude of EMG signals was computed from onset to various time points to align with torque data (e.g. $VL_{0\text{-}50}$ for RMS value from VL EMG onset to 50 ms). These values were normalized to RMS EMG amplitude generated during ramp MVIC contractions (matched by leg and interval), in a 500 ms window centered at peak torque. For both torque and surface EMG data, the best three of the five recorded trials for each variable were averaged to create a single reported value for each leg and interval. A representative example of a voluntary RTD trial with torque and EMG signals is depicted in Figure 2.4.

### Data Analysis

All statistical analyses were performed using IBM SPSS version 21.0 (IBM Corporation, Armonk, NY). Descriptive statistics were calculated for each variable. The assumption of

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normality (assessed by Shapiro-Wilk's test) was violated for a number of RTD variables, and thus, nonparametric statistics were used. The Wilcoxon Signed-Ranks test was used to evaluate side to side asymmetries at each time point for RTD variables. Friedman's ANOVA followed by post hoc tests with Wilcoxon Signed-Ranks (Bonferroni correction) was utilized to evaluate changes in involved leg RTD over time and to evaluate differences between percentage deficits in strength and RTD at each interval. A Spearman’s correlation was performed to evaluate the associations between quadriceps volume, strength, RTD, and subjective knee function. A significance level of $\alpha = .05$ was used for all analyses.

## Results

### Subjects

All subjects underwent partial meniscectomy performed by one of five fellowship trained University of Iowa Sports Medicine surgeons. The medial meniscus was debrided in 15 subjects and the lateral meniscus debrided in five subjects. A mean of 5.4 ± 4.0 months (range 0.5 -16 months) existed between onset of symptoms and date of surgery (one outlier of 50 months was excluded from this calculation). Subjects completed the pre-test session an average of 4.3 ± 3.4 days prior to surgery, the initial (2 week) post-test session 15.8 ± 2.6 days post-surgery, and the final (5 week) test session 35 ± 5.8 days post-surgery.

### Quadriceps Volume, Voluntary Strength and RTD

Significant differences were observed by side for all lower extremity muscle volume, strength and voluntary RTD variables (Table 2.1). Strength, muscle volume, and RTD of the involved leg were all significantly lower than the uninvolved leg. When normalized to MVIC, MRTD of the involved leg was significantly lower at 2 weeks post-surgery. MRTD and $\mathrm{TTI}_{200}$

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deficits were significantly greater than deficits in knee extensor strength at 2 weeks post-surgery. Deficits in $RTD_{20\text{-}80}$ were significantly greater than MVIC deficits at all test intervals. Knee extensor MVIC of both legs was significantly greater at 5 weeks post-surgery than pre-surgery. Involved leg normalized RTD variables were lower at 2 weeks and 5 weeks post-surgery than prior to surgery, but these differences were not statistically significant.

### Evoked Strength and RTD

There were significant differences between limbs in the peak torque elicited by the doublet stimulation protocol at 5 weeks post-surgery and in the maximum RTD elicited at 2 and 5 weeks post-surgery. When normalized to the peak torque of the evoked trials, RTD was not significantly different between the involved and uninvolved limbs at any time period. The ratio of normalized voluntary to evoked MRTD was significantly greater in the uninvolved limb at 2 weeks post-surgery (Table 2.1).

### Quadriceps EMG and EMD

RMS EMG of the quadriceps muscles was significantly lower at 2 weeks post-surgery for all VL and VM RTD intervals. There were no significant differences preoperatively. VL and VM RMS EMG side to side deficits were more pronounced than deficits in RF EMG. At 5 weeks post-surgery, only $VL_{0\text{-}200}$ was significantly lower in the involved leg (Table 2.2).

EMD of the VL and VM was significantly greater in the involved leg at 2 weeks post-surgery (VL: Involved Leg 83 ms, Uninvolved Leg 68 ms, $p = .002$; VM: Involved Leg 84 ms, Uninvolved Leg 71 ms, $p = .010$). EMD of the RF was significantly greater in the involved leg at 5 weeks post-surgery (Involved Leg 81 ms, Uninvolved Leg 76 ms, $p = .048$). There were no significant differences in EMD of the involved limb between testing periods (Table 2.2).

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### Voluntary Activation

VA was significantly lower in the involved leg prior to surgery.  There were no significant differences following surgery (Table 2.2).

### Relationships between Strength, RTD, and EMG Variables

Positive correlations between MVIC and RTD were stronger for later phase RTD variables (e.g., $TTI_{200}$) than early phase RTD variables (e.g., $TTI_{50}$) at all measurement periods (Table 2.3).  When RTD variables were normalized to peak torque, there were no correlations between MVIC and RTD.  Changes in involved leg MVIC between any of the test periods were not correlated with changes in RTD variables (Table 2.5).

Normalized RTD variables (e.g., $T_{50}$) were generally strongly positively correlated with quadriceps RMS EMG values (Table 2.4).  Changes in voluntary quadriceps RMS EMG were also positively correlated with changes in voluntary RTD variables from pre-surgery to post-surgery and from 2 to 5 weeks post-surgery, demonstrating that improvements in the ability to rapidly activate the quadriceps muscles were associated with improvements in voluntary knee extensor RTD.  Changes in MVIC were not correlated with changes in quadriceps RMS EMG variables (Table 2.6).

### Subjective Knee Function

KOOS4 scores averaged 47.2 pre-surgery, 51.8 at 2 weeks post-surgery, and 68.2 at 5 weeks post-surgery.  Side to side deficits in voluntary RTD variables were negatively correlated with KOOS scores at 2 and 5 weeks post-surgery.  Thus, greater side to side asymmetries in RTD variables were associated with lower ratings of subjective knee function.  These correlations were significant, while correlations between quadriceps volume, MVIC and KOOS scores were not significant (Table 2.7).

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Increases in involved leg voluntary RTD between 2 and 5 weeks post-surgery were positively correlated with increases in KOOS Sports-Recreation scores in the same time period (Spearman's $r_s = .472$). These correlations were significant, but no other correlations between increases or decreases in involved leg variables and changes in KOOS scores between any of the measurement periods were significant.

WOMET-Total scores averaged 47.7 pre-surgery, 62.5 at 2 weeks post-surgery, and 79.9 at 5 weeks post-surgery. Side to side deficits in voluntary RTD variables, quadriceps volume, and MVIC were negatively correlated with WOMET scores following surgery, but none of these correlations reached significance (Table 2.7). UCLA Activity scores averaged 6.6 pre-surgery, 4.2 at 2 weeks post-surgery, and 5.7 at 5 weeks post-surgery. Side to side deficits in involved leg quadriceps volume and performance variables were negatively correlated with UCLA scores, but only the correlation with MRTD at 2 weeks post-surgery reached significance (Table 2.7).

## Discussion

This novel investigation of the neuromuscular changes related to rapid force production from pre-operative assessment throughout the early postoperative period following APM adds to our understanding of the effects of lower extremity injury and surgery on quadriceps neuromuscular function. Deficits in the ability to rapidly activate muscle and modulate muscle force are indicative of neuromuscular system dysfunction that may contribute to abnormal movement biomechanics and performance of daily activities. Understanding both the causes and the consequences of these deficits is crucial to our ability to provide better treatment with specifically targeted interventions.

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The hypotheses of this investigation were primarily supported. Patients in this study who underwent APM presented with significant side to side deficits in the ability to rapidly produce knee extensor torque both prior to and in the early postoperative period following arthroscopic knee surgery. Side-to-side asymmetries in RTD variables were greater than asymmetries in peak torque development at each measurement period, though not all of these differences were significant. This is understandable as measures of rapid torque development are more variable than peak torque.(Bemben et al., 1992, Buckthorpe et al., 2012, Clark et al., 2007, Tillin et al., 2011) There were significant deficits in rapid quadriceps activation at the initial post-surgery measurement period that were strongly correlated with the deficits in rapid torque production. In addition, improvements in rapid quadriceps muscle activation after surgery were positively associated with improvements in the ability to rapidly develop knee extensor torque. Lastly, deficits in RTD following APM were more closely related to subjective knee function than measures of maximal voluntary strength or quadriceps muscle volume.

There are a number of potential contributing factors to the deficits in rapid torque production following knee injury and arthroscopy. Maximum strength and RTD are strongly positively correlated,(Aagaard et al., 2002a) particularly for later phase RTD variables.(Andersen and Aagaard, 2006) In this subject population, normalized knee extensor RTD deficits were in the range of 10-15%, indicating that the peak torque producing capability of the muscle accounts for some, but not all, of the deficits in RTD.

At 2 weeks post-surgery, the ratio of normalized voluntary to evoked maximum rapid torque production was significantly greater in the uninvolved limb (41.4% to 35.3%). This deficit suggests that impaired centrally mediated neural function of the involved quadriceps may limit RTD post-surgery. A slightly smaller deficit existed at 5 weeks post-surgery (3.2% greater

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in the uninvolved limb), although this difference was not statistically significant. These asymmetries suggest that these patients could improve their ability to rapidly produce knee extensor torque by increasing rapid voluntary neural activation in the early post-surgical period.

The positive relationship between quadriceps volume and MVIC was notably stronger than the relationship between quadriceps volume and RTD. Despite mitigation of the deficits in quadriceps muscle volume and peak torque production (side-to-side asymmetries were lower at 5 weeks post operatively than prior to surgery), deficits in voluntary RTD at 5 weeks post-surgery were equal to or greater than pre-surgical deficits. These findings suggest that deficits in central mechanisms controlling fast neuromuscular activation persisted despite gains in quadriceps size and strength.

The intrinsic contractile properties of a muscle are one determinant of the ability to rapidly develop joint torque. MRTD recorded during evoked contractions was significantly greater in the uninvolved limb at 2 and 5 weeks post-surgery. However, when normalized to peak torque, evoked MRTD was not significantly different between legs, indicating that peripherally, the differences in the muscle properties accounting for greater rapid torque production of the uninjured limb were due to greater peak torque production. Similar findings were noted by Tillin et al. when comparing groups of athletes and untrained individuals. Intrinsic contractile properties (elicited with electrical stimulation) of the muscle were similar between groups, and greater rapid force production in athletes was almost entirely accounted for by greater neural activation in the very early period of a voluntary contraction.(Tillin et al., 2010)

This investigation was not designed to elucidate the specific neural processes moderating the changes in quadriceps RTD following meniscus injury and APM. Increased agonist neural drive, likely due to increased motor unit discharge rate, double discharges, or improved motor

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unit synchronization at the onset of contraction can all result in improved capacity to rapidly develop force.(Aagaard et al., 2002a, Barry et al., 2005, Hakkinen et al., 1985, Van Cutsem et al., 1998, Desmedt and Godaux, 1977, Duchateau and Baudry, 2014) Elevated V-wave and H-reflex responses following a period of training coincide with improvements in rapid force production(Aagaard et al., 2002c, Holtermann et al., 2007a) and reflect possible increases in motoneuron excitability and/or decreases in presynaptic inhibition.(Geertsen et al., 2008) Recent investigations indicate that early phase RTD is primarily controlled by central mechanisms,(Tillin et al., 2012) and that supraspinal neural drive and resting recurrent inhibition are significant predictors of RTD.(Johnson et al., 2014) This very initial period of force/torque development and muscle activation (from 0 to 50 ms) may be the most critical for optimal function.(Aagaard et al., 2002a, de Ruiter et al., 2006, Chang et al., 2014)

Stiffness of the MTU can also have a significant effect on RFD, with increasing tendon stiffness being positively related to both RFD and jump height and greater fascicle length resulting in greater possible RFD through increased maximal shortening velocity.(Bojsen-Moller et al., 2005, Reeves et al., 2003, Tillin et al., 2012, Waugh et al., 2013) Decreases in muscle and tendon loading after knee arthroscopy may alter MTU mechanical properties(Reeves et al., 2005) and could contribute to changes in RTD following APM.

Greater side to side deficits in knee extensor RTD were significantly correlated with decreased KOOS and WOMET scores following APM. Conversely, correlations between deficits in quadriceps volume or strength and outcomes scores were weaker and did not reach significance. This is in agreement with the results of previous investigations exploring relationships between subjective knee function and strength/rapid quadriceps performance following ACL reconstruction and TKA.(Hsieh et al., 2014, Maffiuletti et al., 2010) Future

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investigations should attempt to determine if resolving the deficits in RTD results in improved patient-based outcomes.

An interesting finding in this investigation was that quadriceps EMD was significantly greater in the involved limb post-operatively. EMD is thought to be primarily influenced by stretching of the series elastic component, calcium kinetics and cross-bridge formation, and conduction of the action potential.(Cavanagh and Komi, 1979) Previously published investigations have presented conflicting evidence regarding EMD of the knee extensors following surgery. Kaneko et al. reported increased quadriceps EMD in people with previous ACL reconstruction (Kaneko et al., 2002) while Georgoulis and colleagues found no alterations in quadriceps EMG following ACL repair.(Georgoulis et al., 2005) The conflicting findings reported by these two groups could be explained by the time from surgery (shorter in the Kaneko et al. study), graft type, measurement technique and equipment, or methods of defining signal onset and calculating EMD.(Tillin et al., 2013) By increasing the delay prior to the application of muscle tension to bone, greater EMD could be a limiting factor in the performance of activities requiring rapid muscle activation. EMD was correlated with RTD variables in this investigation, similar to previous research.(Zhou et al., 1995) This could indicate that changes in the stiffness of series viscoelastic components or excitation-contraction coupling of the knee extensors contribute to the RTD deficits found in this investigation.(Kaneko et al., 2002, Kubo et al., 2001) The EMD values presented in this study are notably longer than those reported by other groups.(Kaneko et al., 2002, Tillin et al., 2010, Zhou et al., 1995) This could be due to the stiffness of the knee extensor torque measurement system we used (discussed as a limitation below) or the signal sampling and processing techniques utilized.

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The side-to-side asymmetries and changes over time in quadriceps EMG were not equal among the individual quadriceps muscles. The deficits in rapid muscle activation were more pronounced in the VM and VL than the RF. This is in agreement with the results of previously published investigations which indicate that morphological changes of the RF (as a biarticular muscle) following knee injury/surgery are not as significant as variations in the uniarticular knee extensors.(Macleod et al., 2014, Williams et al., 2005a, Williams et al., 2005c) In addition, Williams et al. previously demonstrated that alterations in the specificity of muscle actions in patients prior to and following ACL reconstruction were greater in the VL and VM than the RF, indicating more significant neuromuscular deficits in the vasti muscles in relation to knee injury or surgery.(Williams et al., 2003, Williams et al., 2005b)

The clinical implications of this investigation and potential for future work in this area are significant. Typical daily activities (and sports movements) are characterized by rapid muscle activation and relaxation. Humans rarely, if ever, utilize peak muscle force in performing typical activities. Evidence indicates that sustained neuromuscular deficits contribute to abnormal function and movement biomechanics. The results of this study suggest that designing interventions to resolve the deficits in rapid muscle activation/torque production following knee injury and/or surgery may assist in restoring normal neuromuscular function and could improve outcomes.

Future investigations will seek to further explore the neuromuscular mechanisms and clinical relevance of these findings, as well as study populations with musculoskeletal trauma that is associated with greater quadriceps neuromuscular deficits, such as ACL injury. This work has the potential to alter evaluation and rehabilitation practices and improve the treatment of people suffering from musculoskeletal injury.

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The authors recognize the limitations of this work. The quality of the surgical procedure may have varied between practitioners and could have had an effect on individual outcomes. Only subjects undergoing APM were included in this study. People who underwent other arthroscopic procedures (e.g. loose body removal, fat pad or synovial debridement) were excluded, and the results of this study may not be applicable to these populations. An isokinetic dynamometer with standard lower leg attachments was used to collect knee extensor torque data. Pilot testing in our lab indicated that using a cushioned shin pad may increase the recorded torques during RTD trials in the early portion of the contraction due to the deformation in the pad attached to the lower leg adapter. Ideally, a system with less compliance would be utilized to perform RTD trials.(de Ruiter et al., 2004a) This effect was notable only in the very early portion of the contraction (0-50 ms), which is why torque variables less than 50 ms were not analyzed in this data set. As all outcomes were measures of comparison between limbs or between collection periods, any influence of this compliance on RTD measurements does not affect the results presented.

In this investigation the use of the uninvolved limb served as a within-subjects control, but evidence indicates that unilateral knee injury and/or surgery can result in bilateral deficits in quadriceps strength and neuromuscular function.(Urbach et al., 2001) Therefore, if compared to uninjured controls, the deficits in RTD and quadriceps muscle activation in this population may be more substantial than the side to side asymmetries reported here.(Knezevic et al., 2014) Lastly, subjects in this investigation were also part of a larger group that completed various quadriceps training protocols following APM. However, there were no significant differences in measures of rapid torque production or muscle activation between treatment groups. All subjects completed guided quadriceps exercises in the early post-operative period, and the greatest

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potential effect on the results presented in this paper is the mitigation of deficits in rapid torque production. Thus, the quadriceps deficits presented in this report are likely to be even greater in people who do not perform focused rehabilitation following APM.

## Conclusion

The results of this study indicate that people undergoing APM have significant deficits in the ability to rapidly produce knee extensor torque. Side to side asymmetries in quadriceps EMG, and the relationships between neural activation and RTD variables over time suggest that neural mechanisms are the primary limitation of rapid voluntary quadriceps action following knee arthroscopy. The inability to quickly develop or modulate quadriceps force may have significant functional consequences. Clinicians should be aware of the neuromuscular deficits following arthroscopic knee procedures and consider implementing treatment strategies that mitigate deficits in the ability to rapidly activate the quadriceps.

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Table 2.1: Knee extensor voluntary and evoked strength/RTD variables by leg prior to surgery and at 2 and 5 weeks post-surgery

| | **Pre Test** | | | | **2 wk post surgery** | | | | **5 wk post surgery** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Variable** | Involved | Uninvolved | Deficit | p Value | Involved | Uninvolved | Deficit | p Value | Involved | Uninvolved | Deficit | p Value |
| Quadriceps Volume ($cm^3$) | 1636.1 ± 527 | 1735.9 ± 541.6 | 5.7% | ***0.001*** | 1620.3 ± 514.9 | 1731.7 ± 531.3 | 6.4% | ***0.001*** | 1669.5 ± 534.2 | 1751.2 ± 542.6 | 4.7% | ***0.007*** |
| Knee Extension MVIC (Nm/kg) | 2.69 ± 0.8 | 3.1 ± 0.9 | 13.4% | ***< 0.001*** | 2.72 ± 0.9 | $^{\#}$3.28 ± 1.0 | 17.0% | ***< 0.001*** | $^{*}$3.0 ± 1.0 | $^{*}$3.39 ± 1.0 | 11.3% | ***0.001*** |
| Specific Torque ($Nm/cm^3$) | 0.129 ± 0.02 | 0.140 ± 0.02 | 7.9% | ***0.012*** | 0.131 ± 0.03 | 0.148 ± 0.02 | 11.5% | ***0.001*** | $^{*}$0.140 ± 0.03 | $^{*}$0.152 ± 0.02 | 7.7% | ***0.002*** |
| Voluntary MRTD (Nm/s) | 2292.5 ± 818.4 | 2758.2 ± 948.8 | 16.9% | ***0.002*** | 2045.3 ± 700.7 | 2921.8 ± 841.7 | $^{\$}$30.0% | ***< 0.001*** | 2166.5 ± 752.5 | 2766.4 ± 796.1 | 21.7% | ***< 0.001*** |
| Voluntary $MRTD_{NORM}$ | 11.6 ± 4.6 | 12.0 ± 4.5 | 3.4% | 0.654 | 10.3 ± 3.6 | 12.1 ± 3.8 | 15.0% | ***0.015*** | 10.1 ± 3.9 | $^{*}$11.2 ± 3.7 | 9.7% | 0.067 |
| Evoked MRTD (Nm/s) | 2200.5 ± 1071.3 | 2257.1 ± 921.5 | 2.5% | 0.074 | 2109.6 ± 905.3 | 2223.3 ± 908.8 | 5.1% | ***0.023*** | 2081.7 ± 921.3 | 2273.4 ± 864.8 | 8.4% | ***0.01*** |
| Evoked $MRTD_{NORM}$ | 30.8 ± 8.1 | 32.0 ± 8.5 | 3.9% | 0.086 | 31.3 ± 9.8 | 32.3 ± 11.9 | 3.2% | 0.145 | 32.2 ± 9.7 | 32.6 ± 9.9 | 1.2% | 0.709 |
| $Vol_{NORM}$/$Evoked_{NORM}$ MRTD (%) | 40.2 ± 19.4% | 39.6 ± 16.4% | -1.5% | 0.911 | 35.3 ± 14.0% | 41.4 ± 16.7% | 14.8% | ***0.014*** | 33.8 ± 14.1% | 37.0 ± 14.3% | 8.9% | 0.117 |
| $RTD_{20-80}$ (Nm/s) | 768.3 ± 361.4 | 1000.9 ± 401.7 | $^{\$}$23.2% | ***0.001*** | 719.1 ± 375.7 | 1039 ± 411.4 | $^{\$}$30.8% | ***< 0.001*** | 770.7 ± 344.5 | 994.7 ± 378.9 | $^{\$}$22.5% | ***< 0.001*** |
| $T_{50}$ (% of MVIC) | 31.7 ± 12.5% | 33.7 ± 10.4% | 6.0% | 0.550 | 27.7 ± 11.5% | 31.7 ± 11.7% | 12.5% | 0.167 | 27.0 ± 12.0% | 30.2 ± 9.9% | 10.5% | 0.108 |
| $T_{100}$ (% of MVIC) | 52.0 ± 12.1% | 57.8 ± 12.3% | 10.1% | ***0.005*** | 48.9 ± 10.7% | 57.1 ± 9.8% | 14.4% | ***0.023*** | 49.5 ± 10.4% | 54.2 ± 10.1% | 8.7% | 0.067 |
| $T_{200}$ (% of MVIC) | 72.0 ± 11.9% | 78.0 ± 11.6% | 7.8% | ***0.004*** | 69.1 ± 12.6% | 78.8 ± 7.3% | 12.3% | ***0.003*** | 69.6 ± 8.4% | 75.3 ± 9.1% | 7.6% | ***0.028*** |
| $TTI_{50}$ (Nm*s) | 1.28 ± 0.6 | 1.64 ± 0.5 | 22.0% | ***0.005*** | 1.15 ± 0.5 | 1.54 ± 0.6 | 25.4% | ***0.040*** | 1.13 ± 0.5 | 1.5 ± 0.5 | 24.8% | ***0.003*** |
| $TTI_{100}$ (Nm*s) | 5.67 ± 2.5 | 7.2 ± 2.5 | 21.3% | ***0.002*** | 5.17 ± 1.8 | 7.05 ± 2.5 | 26.6% | ***0.001*** | 5.39 ± 2.1 | 6.95 ± 2.2 | 22.5% | ***< 0.001*** |
| $TTI_{200}$ (Nm*s) | 18.3 ± 7 | 22.9 ± 8.3 | $^{\$}$20.2% | ***< 0.001*** | 17.7 ± 6.7 | 23.7 ± 8 | $^{\$}$25.3% | ***< 0.001*** | 18.8 ± 7 | 23.3 ± 7.4 | 19.1% | ***< 0.001*** |
| Knee Flexion MVIC (Nm/kg) | 0.93 ± 0.3 | 1.05 ± 0.3 | 11.4% | ***0.011*** | 0.99 ± 0.3 | 1.07 ± 0.3 | 7.5% | 0.059 | 1.0 ± 0.3 | 1.09 ± 0.3 | 7.3% | 0.059 |

**Abbreviations:** MVIC, maximum voluntary isometric contraction; MRTD, maximum rate of torque development; $MRTD_{NORM}$, normalized maximum rate of torque development (voluntary trials normalized to MVIC, evoked trials normalized to peak evoked torque); $RTD_{20-80}$, rate of torque development from 20 to 80% of peak torque; $T_{50/100/200}$, torque at 50/100/200 ms (expressed as % of MVIC); $TTI_{50/100/200}$, torque time integral from 0-50/0-100/0-200 ms.

*significant differences between pre surgery value and 5 week post-surgery value ($p < .05$)

$^{\#}$significant difference between pre surgery value and 2 week post-surgery value ($p < .05$)

$^{\$}$significant difference between RTD percentage deficit and Knee Extension MVIC percentage deficit at specified testing period ($p < .05$)

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Table 2.2: Neuromuscular activation characteristics of the quadriceps muscles prior to surgery and at 2 and 5 weeks post-surgery

| | **Pre Test** | | | | **2 wk post surgery** | | | | **5 wk post surgery** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Variable** | Involved | Uninvolved | Deficit | p Value | Involved | Uninvolved | Deficit | p Value | Involved | Uninvolved | Deficit | p Value |
| $VL_{0-50}$ (%$EMG_{MVIC}$) | 58.5 ± 36.7% | 68.6 ± 51.2% | 14.8% | 0.627 | 47.0 ± 25.3% | 67.6 ± 28.2% | 30.5% | ***0.006*** | 48.1 ± 27.3% | 61.1 ± 36.7% | 21.3% | 0.108 |
| $RF_{0-50}$ (%$EMG_{MVIC}$) | 53.0 ± 35.1% | 51.2 ± 29.7% | -3.4% | 0.550 | 46.1 ± 24.6% | 48.5 ± 19.9% | 5.1% | 0.526 | 36.1 ± 20.8% | 41.6 ± 18.6% | 13.1% | 0.332 |
| $VM_{0-50}$ (%$EMG_{MVIC}$) | 69.8 ± 38.4% | 71.6 ± 45.1% | 2.4% | 0.970 | 48.9 ± 20.6% | 72.5 ± 35.8% | 32.6% | ***0.021*** | 54.5 ± 35.8% | 55.2 ± 20.3% | 1.2% | 0.794 |
| $VL_{0-100}$ (%$EMG_{MVIC}$) | 79.1 ± 37.2% | 89.7 ± 45.8% | 11.9% | 0.550 | 70.4 ± 24.4% | 92.7 ± 26.6% | 24.1% | ***0.012*** | 68.9 ± 25.4% | 81.7 ± 42.2% | 15.6% | 0.191 |
| $RF_{0-100}$ (%$EMG_{MVIC}$) | 69.7 ± 33.3% | 71.4 ± 26.3% | 2.4% | 0.970 | 64.0 ± 24.7% | 75.3 ± 22.1% | 15.1% | 0.167 | 57.5 ± 28.6% | 64.3 ± 22.7% | 10.5% | 0.455 |
| $VM_{0-100}$ (%$EMG_{MVIC}$) | 86.9 ± 38.8% | 95.6 ± 40.2% | 9.1% | 0.279 | 68.5 ± 22.5% | 103.6 ± 30.4% | 33.9% | ***0.001*** | 68.8 ± 31.3% | 78.7 ± 24.0% | 12.6% | 0.263 |
| $VL_{0-200}$ (%$EMG_{MVIC}$) | 89.8 ± 32.1% | 100.9 ± 35.1% | 11.0% | 0.411 | 80.6 ± 24.4% | 104.8 ± 26.3% | 23.1% | ***0.009*** | 75.6 ± 22.9% | 92.6 ± 33.6% | 18.4% | ***0.025*** |
| $RF_{0-200}$ (%$EMG_{MVIC}$) | 80.1 ± 33.2% | 85.6 ± 24.8% | 6.4% | 0.455 | 72.4 ± 23.4% | 86.1 ± 18.5% | 16.0% | 0.033 | 69.0 ± 26.9% | 75.8 ± 19.3% | 9.0% | 0.232 |
| $VM_{0-200}$ (%$EMG_{MVIC}$) | 96.6 ± 37.5% | 107.1 ± 31.3% | 9.8% | 0.263 | 79.4 ± 27.8% | 117.7 ± 20.8% | 32.5% | ***0.001*** | 81.4 ± 26.7% | 91.8 ± 23.9% | 11.4% | 0.296 |
| VL EMD (ms) | 76.3 ± 10.2 | 75.5 ± 10.9 | 1.0% | 0.411 | 82.7 ± 18.5 | 68.0 ± 12.2 | 17.8% | ***0.002*** | 76.4 ± 13.2 | 72.0 ± 8.7 | 5.8% | 0.097 |
| RF EMD (ms) | 77.7 ± 12.0 | 78.4 ± 12.2 | -0.9% | 1.000 | 80.3 ± 20.6 | 73.5 ± 15.3 | 8.5% | 0.083 | 81.3 ± 16.0 | 76.0 ± 8.4 | 6.6% | ***0.048*** |
| VM EMD (ms) | 76.0 ± 11.3 | 76.9 ± 12.5 | -1.2% | 0.601 | 84.0 ± 21.9 | 71.0 ± 16.4 | 15.5% | ***0.010*** | 74.2 ± 14.2 | 71.9 ± 9.5 | 3.0% | 0.263 |
| Voluntary Activation (%) | 85.9 ± 9.8% | 90.6 ± 8.1% | 5.2% | ***0.005*** | 90.6 ± 11.4% | 94.0 ± 4.8% | 3.5% | 0.057 | 91.9 ± 6.4% | 93.7 ± 5.1% | 2.0% | 0.108 |

**Abbreviations:** $VL_{0-50/0-100/0-200}$, root mean square (RMS) amplitude of the vastus lateralis from 0 to 50/100/200 ms; $RF_{0-50/0-100/0-200}$; RMS amplitude of the rectus femoris from 0 to 50/100/200 ms; $VM_{0-50/0-100/0-200}$, RMS amplitude of the vastus medialis from 0 to 50/100/200 ms; VL EMD, electromechanical delay of the vastus lateralis; RF EMG, electromechanical delay of the rectus femoris; VM EMD, electromechanical delay of the vastus medialis.

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Table 2.3: Correlations (Spearman's rs) between involved leg quadriceps volume, knee extensor strength, and RTD variables prior to surgery and at 2 and 5 weeks post-surgery

| | QV | | | $TTI_{50}$ | | | $TTI_{100}$ | | | $TTI_{200}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pre | 2 wk | 5 wk | Pre | 2 wk | 5 wk | Pre | 2 wk | 5 wk | Pre | 2 wk | 5 wk |
| MVIC | .863** | .872** | .905** | 0.308 | -0.020 | 0.191 | .649** | .701** | .561* | .891** | .937** | .929** |
| MRTD | 0.372 | .600** | .492* | .851** | 0.254 | .715** | .884** | .656** | .686** | .751** | .792** | .611** |
| QV | - | - | - | 0.080 | -0.223 | 0.150 | .447* | .486* | .534* | .711** | .826** | .836** |

**Abbreviations:** QV, quadriceps volume ($cm^3$); MVIC, maximum voluntary isometric contraction; MRTD, maximum rate of torque development; $TTI_{50/100/200}$, torque time integral from 0-50/0-100/0-200 ms.

*Correlation is significant at the 0.05 level (2-tailed)

**Correlation is significant at the 0.01 level (2-tailed)

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Table 2.4: Correlations (Spearman's rs) between involved leg quadriceps surface EMG and normalized RTD variables prior to surgery and at 2 and 5 weeks post-surgery

| $T_{50}$ (% of MVIC) | | | $T_{100}$ (% of MVIC) | | | $T_{200}$ (% of MVIC) | | |
|---|---|---|---|---|---|---|---|---|
| $VL_{0\text{-}50}$ | Pre | .699** | $VL_{0\text{-}100}$ | Pre | .723** | $VL_{0\text{-}200}$ | Pre | .659** |
| | 2 wk | 0.417 | | 2 wk | .690** | | 2 wk | .659** |
| | 5 wk | .597** | | 5 wk | 0.223 | | 5 wk | .448* |
| $RF_{0\text{-}50}$ | Pre | .606** | $RF_{0\text{-}100}$ | Pre | .570** | $RF_{0\text{-}200}$ | Pre | .635** |
| | 2 wk | .567** | | 2 wk | .478* | | 2 wk | .486* |
| | 5 wk | .529* | | 5 wk | 0.134 | | 5 wk | 0.356 |
| $VM_{0\text{-}50}$ | Pre | .660** | $VM_{0\text{-}100}$ | Pre | .465* | $VM_{0\text{-}200}$ | Pre | .755** |
| | 2 wk | 0.435 | | 2 wk | .681** | | 2 wk | .627** |
| | 5 wk | 0.427 | | 5 wk | 0.347 | | 5 wk | 0.358 |

**Abbreviations:** $T_{50/100/200}$, torque at 50/100/200 ms (expressed as % of MVIC); $VL_{0\text{-}50/0\text{-}100/0\text{-}200}$, root mean square (RMS) amplitude of the vastus lateralis from 0 to 50/100/200 ms; $RF_{0\text{-}50/0\text{-}100/0\text{-}200}$; RMS amplitude of the rectus femoris from 0 to 50/100/200 ms; $VM_{0\text{-}50/0\text{-}100/0\text{-}200}$, RMS amplitude of the vastus medialis from 0 to 50/100/200 ms.
*Correlation is significant at the 0.05 level (2-tailed)
**Correlation is significant at the 0.01 level (2-tailed)

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Table 2.5: Correlations (Spearman's rs) between changes in involved leg quadriceps volume, knee extensor strength, and RTD variables from pre – 2 weeks post-surgery, and from 2 – 5 weeks post-surgery

| | QV | | $TTI_{50}$ | | $TTI_{100}$ | | $TTI_{200}$ | |
|---|---|---|---|---|---|---|---|---|
| | Pre to 2 wk | 2 wk to 5 wk | Pre to 2 wk | 2 wk to 5 wk | Pre to 2 wk | 2 wk to 5 wk | Pre to 2 wk | 2 wk to 5 wk |
| MVIC | .586** | -0.027 | 0.011 | 0.245 | 0.133 | 0.223 | 0.276 | 0.201 |
| MRTD | 0.069 | -0.092 | .505* | 0.313 | .709** | .487* | .797** | .663** |

**Abbreviations:** QV, quadriceps volume ($cm^3$); MVIC, maximum voluntary isometric contraction; MRTD, maximum rate of torque development; $TTI_{50/100/200}$, torque time integral from 0-50/0-100/0-200 ms.
*Correlation is significant at the 0.05 level (2-tailed)
**Correlation is significant at the 0.01 level (2-tailed)

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Table 2.6: Correlations (Spearman's rs) between changes in involved leg quadriceps surface EMG, strength and RTD variables from pre – 2 weeks post-surgery, and from 2 – 5 weeks post-surgery

| MVIC | | | MRTD | | | $T_{50}$ (% of MVIC) | | | $T_{200}$ (% of MVIC) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $VL_{0\text{-}100}$ | Pre to 2 wk | -0.018 | $VL_{0\text{-}100}$ | Pre to 2 wk | .766** | $VL_{0\text{-}50}$ | Pre to 2 wk | .615** | $VL_{0\text{-}200}$ | Pre to 2 wk | .585** |
| | 2 wk to 5 wk | -0.030 | | 2 wk to 5 wk | .549* | | 2 wk to 5 wk | .490* | | 2 wk to 5 wk | 0.409 |
| $RF_{0\text{-}100}$ | Pre to 2 wk | -0.442 | $RF_{0\text{-}100}$ | Pre to 2 wk | 0.313 | $RF_{0\text{-}50}$ | Pre to 2 wk | .618** | $RF_{0\text{-}200}$ | Pre to 2 wk | .586** |
| | 2 wk to 5 wk | 0.166 | | 2 wk to 5 wk | 0.429 | | 2 wk to 5 wk | .525* | | 2 wk to 5 wk | 0.405 |
| $VM_{0\text{-}100}$ | Pre to 2 wk | -0.165 | $VM_{0\text{-}100}$ | Pre to 2 wk | 0.317 | $VM_{0\text{-}50}$ | Pre to 2 wk | .669** | $VM_{0\text{-}200}$ | Pre to 2 wk | .716** |
| | 2 wk to 5 wk | -0.113 | | 2 wk to 5 wk | 0.337 | | 2 wk to 5 wk | 0.442 | | 2 wk to 5 wk | .460* |

**Abbreviations:** MVIC, maximum voluntary isometric contraction; MRTD, maximum rate of torque development; $T_{50/200}$, torque at 50/200 ms (expressed as % of MVIC); $VL_{0\text{-}50/0\text{-}100/0\text{-}200}$, root mean square (RMS) amplitude of the vastus lateralis from 0 to 50/100/200 ms; $RF_{0\text{-}50/0\text{-}100/0\text{-}200}$; RMS amplitude of the rectus femoris from 0 to 50/100/200 ms; $VM_{0\text{-}50/0\text{-}100/0\text{-}200}$, RMS amplitude of the vastus medialis from 0 to 50/100/200 ms.

*Correlation is significant at the 0.05 level (2-tailed)

**Correlation is significant at the 0.01 level (2-tailed)

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Table 2.7: Correlations (Spearman's rs) between outcomes scores and side-to-side asymmetries in quadriceps volume, strength and RTD variables at 2 (A) and 5 (B) weeks post-surgery

| **(A)** | **2 wk post surgery** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | KOOS Sports/Rec | | KOOS4 | | WOMET Total | | UCLA | |
| | $r_s$ | p value | $r_s$ | p value | $r_s$ | p value | $r_s$ | p value |
| MVIC | -0.347 | 0.134 | -0.230 | 0.329 | -0.194 | 0.413 | -0.279 | 0.233 |
| MRTD | -0.501 | ***0.025*** | -0.481 | ***0.032*** | -0.329 | 0.157 | -0.460 | ***0.041*** |
| QV | -0.252 | 0.283 | -0.194 | 0.413 | -0.298 | 0.202 | -0.155 | 0.513 |

| **(B)** | **5 wk post surgery** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | KOOS Sports/Rec | | KOOS4 | | WOMET Total | | UCLA | |
| | $r_s$ | p value | $r_s$ | p value | $r_s$ | p value | $r_s$ | p value |
| MVIC | -0.150 | 0.529 | -0.308 | 0.186 | -0.444 | 0.050 | -0.425 | 0.062 |
| MRTD | -0.511 | ***0.021*** | -0.568 | ***0.009*** | -0.438 | 0.054 | -0.443 | 0.050 |
| QV | -0.107 | 0.652 | -0.211 | 0.373 | -0.436 | 0.055 | -0.295 | 0.206 |

**Abbreviations:** MVIC, maximum voluntary isometric contraction; MRTD, maximum rate of torque development; QV, quadriceps volume ($cm^3$); KOOS, Knee Injury and Osteoarthritis Outcome Score; WOMET, Western Ontario Meniscal Evaluation Tool; UCLA, UCLA Activity Score.

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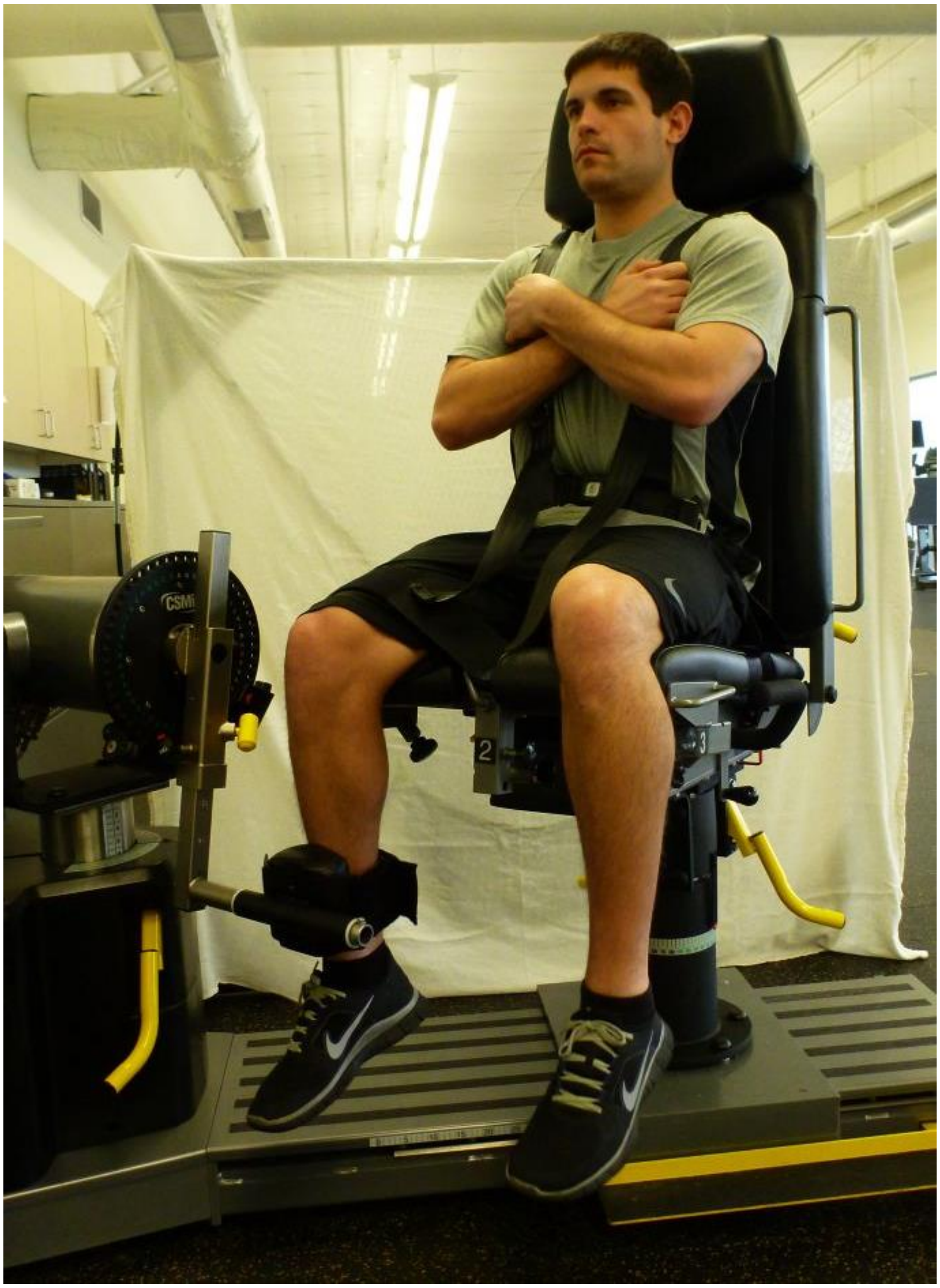

Figure 2.1: Subject positioning for isometric testing of quadriceps muscle contractile properties, strength, activation, and RTD.

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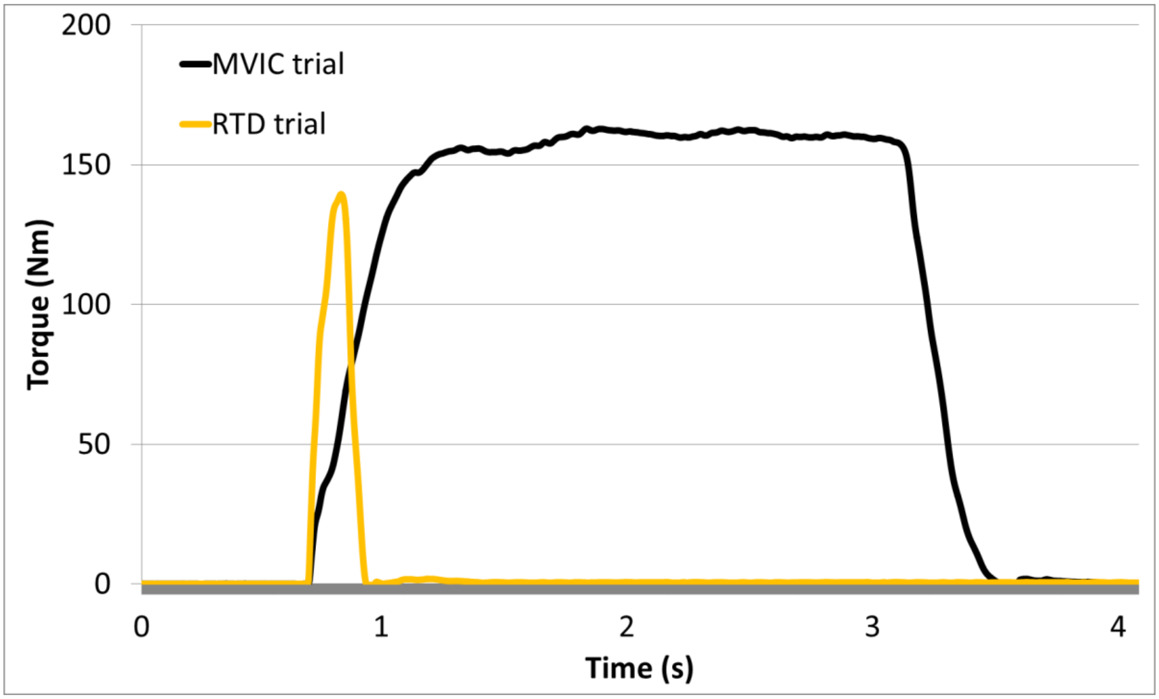

Figure 2.2: Example graphic depicting the torque signals produced by a ramp MVIC contraction and a rapid RTD effort.

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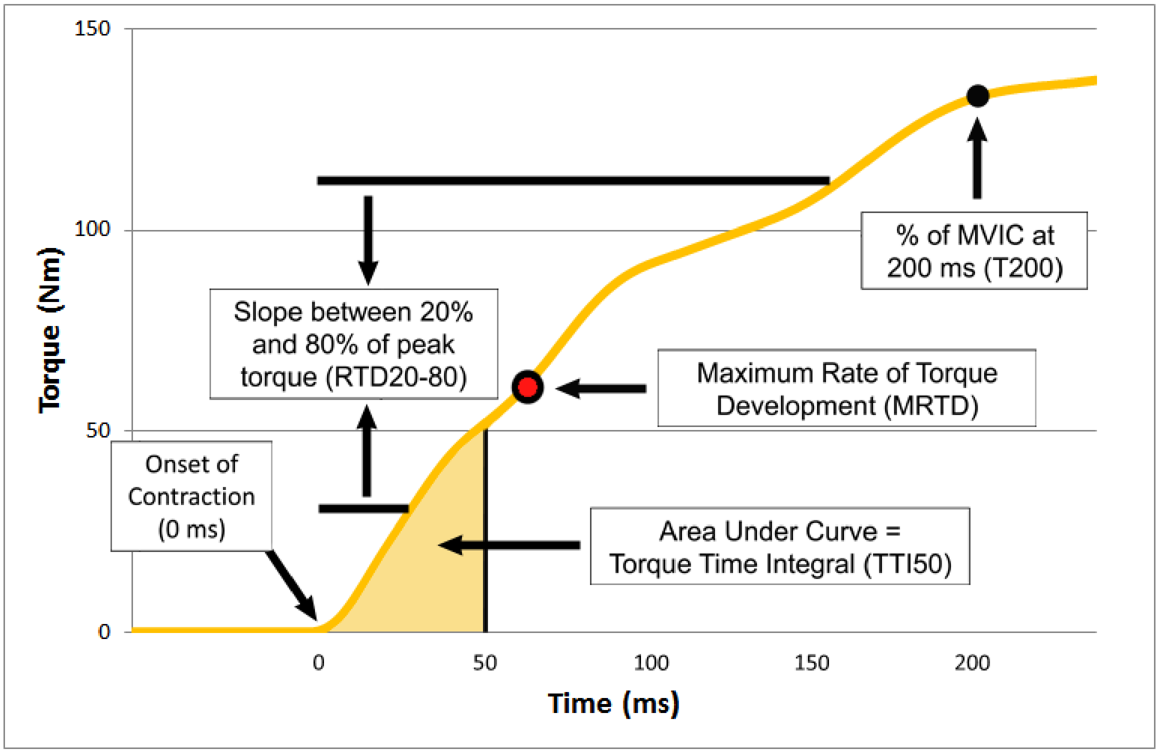

Figure 2.3: Sample torque signal produced by a rapid isometric knee extension RTD contraction illustrating definitions of RTD variables. Onset of contraction was defined as the last data point at which the torque signal either decreased or remained constant from the previous point prior to rising continuously during the initial portion of the contraction. Torque time integrals (TTI) for 0-100 and 0-200 ms were also computed ($TTI_{100}$ and $TTI_{200}$, respectively). Percentage of MVIC torque reached at 50, 100, 200 ms were also calculated ($T_{50}$, $T_{100}$, and $T_{200}$).

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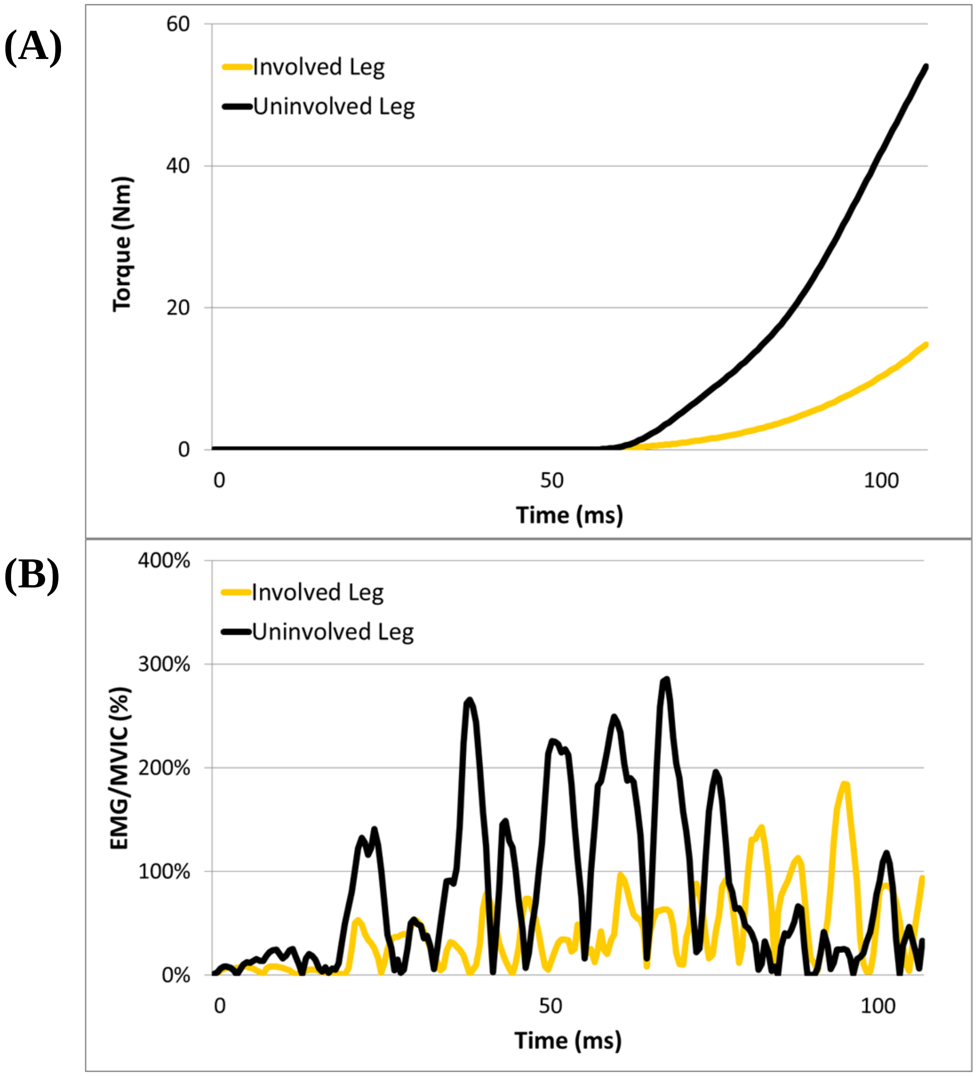

Figure 2.4: Sample torque (A) and rectified VL EMG (B) recordings from the voluntary RTD trials of a representative subject with significant side-to-side RTD asymmetries 2 weeks post-surgery. Recordings are synchronized. EMD is approximately 60 ms in this example.

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# CHAPTER 3

# CLOSED KINETIC CHAIN LOWER EXTREMITY POWER AND NEUROMUSCULAR PERFORMANCE AFTER ARTHROSCOPIC PARTIAL MENISCECTOMY

## Introduction

Throughout a typical day, people perform a variety of activities which require alternating periods of rapid muscle activation and relaxation.  Analysis of electromyography data collected during common activities indicates that the majority of human movement patterns are characterized by short periods of time in which muscles must rapidly develop force to accomplish the desired actions.(Cappellini et al., 2006, Gazendam and Hof, 2007, Rand and Ohtsuki, 2000)

In the fields of strength and conditioning, human physiology, and other related disciplines, studies of muscle performance often include measures of rapid force development, muscle power, or rapid neuromuscular activation.(Abernethy et al., 1995, Bozic et al., 2013, Duchateau et al., 2006, Kamen and Knight, 2004, Tillin et al., 2010)  Conversely, in rehabilitation science literature, muscle performance is typically characterized with basic measurements of peak force generating capability.(Chmielewski et al., 2002, McLeod et al., 2012, Schmitt et al., 2014)  Evaluating only peak strength may be insufficient to obtain important measurements of muscle performance related to the ability to successfully accomplish many tasks and activities.

Peak force measurements are time-independent.  During an isometric contraction, it takes roughly 300-500 ms to generate peak muscle force.(Thorstensson et al., 1976)  Conversely, measuring the rate of muscle activation or force generation creates time-dependent

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characterizations of performance that may be more closely related to function than peak force measurements.(Aagaard, 2003, Aagaard et al., 2002a, de Ruiter et al., 2006)

In elderly populations, power is an important concept in maximizing function and improving performance of typical activities of daily living.(Reid and Fielding, 2012) A variety of functional performance measurements (walking speed, stair ascent, fall history, etc.) have been shown to be more closely related to measures of lower extremity power or rapid force development than peak strength.(Bento et al., 2010, Larsen et al., 2009, Puthoff et al., 2008, Puthoff and Nielsen, 2007) In addition, elderly subjects participating in power training interventions demonstrate improvements in strength, power, and functional performance.(Holsgaard-Larsen et al., 2011, Orr et al., 2006, Piirainen et al., 2014, Sayers and Gibson, 2012) Investigations comparing power training to traditional strength training indicate that power training results in greater improvements in muscle performance and function with similar gains in peak strength.(Sayers and Gibson, 2012, Sayers and Gibson, 2014, Sayers et al., 2012)

From a rehabilitation standpoint, measuring or training power or rapid muscle actions following injury and surgery is largely ignored. During the initial recovery period, slower controlled movements are encouraged, and only in the later phases of rehabilitation are more rapid muscle actions emphasized.(Wilk et al., 2012) This rationale could in fact contribute to the greater deficits in the ability to rapidly activate muscle or generate greater power following injury/surgery, and thus, inhibit recovery of normal neuromuscular function. Two recent investigations support this idea, reporting that 95% of patients 6 months after ACL reconstruction were found to have an abnormal limb symmetry index on three tests of lower

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extremity power and 52% of patients were abnormal 24 months after surgery.(Neeter et al., 2006, Thomee et al., 2012)

Arthroscopic partial meniscectomy (APM) is a very common orthopaedic procedure (Kim et al., 2011), the goal of which is to resolve symptoms attributed to meniscus tear by creating a stable rim. Return to ambulation, work, and daily activities is typically allowed within 2 to 6 weeks of surgery, without formal post-operative physical therapy.(Goodwin and Morrissey, 2003, Lubowitz et al., 2008, Umar, 1997) However, current evidence indicates that people undergoing APM present with deficits in quadriceps neuromuscular performance both prior to (Stensrud et al., 2014) and following surgery (Akima et al., 2008, Ericsson et al., 2006, Glatthorn et al., 2010, Hall et al., 2013, McLeod et al., 2012) that can affect movement biomechanics (Durand et al., 1993, Hall et al., 2013, Moffet et al., 1993) and limit knee-related quality of life.(Roos et al., 2001, Roos et al., 2000)

The rate of force or torque development (RFD/RTD) is a measure of the maximum rate of tension development during an isometric contraction, and can be utilized to measure the rapid force generating capacity of the neuromuscular system.(Wilkie, 1949) RTD is typically measured during open chain isometric efforts of a single joint or muscle group (such as the quadriceps during isometric knee extension). Conversely, muscle power is often calculated during multi-joint movements that may be more similar to typical movement patterns during common functional activities (such as rising from a chair, negotiating stairs, lifting objects overhead, etc.). Similar comparisons could be made between open and closed kinetic chain movements, with closed chain activities typically considered more “functional” due to the similarities with weight bearing activities.(Aalund et al., 2013, Rossi et al., 2007)

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The interaction between open and closed chain measurements of rapid torque development and muscle power in the context of musculoskeletal injury is unclear. The purpose of this investigation was to evaluate closed chain lower extremity power and knee extensor RTD prior to and in the month following arthroscopic meniscal debridement. This is the first study to look at early post-operative measurements of power and rapid muscle activation in patients undergoing arthroscopic knee surgery. This novel investigation provides unique characterizations of neuromuscular function related to rapid torque development preoperatively and in the early postoperative period following APM. The hypotheses of this investigation were:

1) Patients undergoing APM will have significant side to side asymmetries in leg press (LP) strength, power, acceleration, and knee extensor RTD after surgery.
2) LP Power and knee extensor RTD will be more closely associated with patient reported outcomes than peak strength.
3) Subjects will demonstrate greater side to side asymmetries in knee extensor RTD than in LP Power after APM

## Methods

### Subjects

9 people undergoing APM (4 males, 5 females, mean age 34.8 ± 13.2, mean BMI 25.5 ± 2.4) volunteered to participate in this study. All subjects were right leg dominant as defined by the leg they would choose to kick a ball with. Patients treated at The University of Iowa Sports Medicine clinic and indicated for arthroscopic knee surgery with University of Iowa surgeon investigators were candidates for this study. Exclusion criteria included concomitant knee ligament injury or recent fracture, quadriceps muscle rupture, history of neurological disorder, BMI > 40, or any other medical condition which could have compromised patient safety or

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validity of the study results. Subjects completed a basic lower extremity physical examination to confirm eligibility. All subjects were provided with a comprehensive description of study procedures and confirmed their desire to participate. Written consent was obtained using a document approved by the University of Iowa Human Subjects Research Institutional Review Board. Subjects in this study were part of a larger randomized controlled trial investigating the effects of various exercise protocols on quadriceps size and neuromuscular performance following APM. Subjects were randomized to one of three treatment groups, and completed 10 rehabilitation sessions following surgery and prior to the final test session.

### Testing Procedures

Subjects performed a battery of tests and measures prior to surgery and approximately 2 weeks and 5 weeks after surgery with each leg. Tests were carried out in a consistent order at each interval.

### Lower Extremity Power Testing

Two calendar days prior to quadriceps volume measurement and muscle tests, subjects completed a leg press power test utilizing an instrumented leg press device (Keiser A420, Keiser Inc., Fresno, CA) designed to quantify lower extremity power production (Figure 3.1). Subjects were seated with hip and knee angles of approximately 115 and 90 degrees and feet were centered on the pedals. Subjects performed warmup repetitions at low velocity and low resistance to gain familiarity with the device. Subjects then completed one repetition maximum (1RM) testing according to NSCA guidelines.(Miller, 2012)

Subjects were instructed to attempt to extend the knee from the starting position to 0 degrees of flexion. Subjects rested for roughly 1 minute between repetitions until reaching approximately 90% of 1RM value, at which point they rested for roughly 2 minutes between

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repetitions. At subsequent test sessions, subjects performed fewer repetitions at submaximal values as both the researcher and the subject had a more accurate understanding of the subject's attainable 1RM.

After completing 1RM testing, subjects were provided 2 minutes to stand up and rest while data was loaded. Subjects were then re-seated in the chair to perform power repetitions. The uninvolved leg was always tested first. Subjects were instructed to push out against the pedal as fast and as hard as possible. They were provided feedback of the peak power produced on each repetition, through the leg press real time data analysis software.(Staub et al., 2013) Subjects were instructed to attempt to reach the highest possible peak power value. Subjects completed a minimum of three practice repetitions prior to recorded efforts, and were allowed to continue practice trials until they were comfortable completing the task as desired with maximal effort.

Resistance was initially set to 40% of the 1RM value for the leg being testing. Subjects completed a minimum of 5 repetitions, resting for 60 seconds between efforts. Two minutes of rest was provided, followed by completion of the identical testing protocol with resistance set to 70% of the 1RM value for the leg being testing. The rationale for performing power testing at 40 and 70% of 1RM was to characterize power production with an efficient testing design at two points on the force/velocity curve (one high velocity/low force, the other low velocity/high force) which bracket the intersection of force and velocity resulting in peak power for the majority of people.(de Vos et al., 2005, Zbinden-Foncea et al., 2014)

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### Patient-based Outcomes Measures

Subjects completed the WOMET, KOOS, and UCLA activity scores, reliable and accurate patient reported outcomes in this population.(Naal et al., 2009, Roos and Lohmander, 2003, Sihvonen et al., 2012) A pain VAS score was also obtained at each testing session.

### Quadriceps Volume Measurement

Axial T1-weighted images of quadriceps muscle volume were acquired with a Siemens Trio 3T scanner (Siemens Medical Solutions USA, Inc., Malvern, PA). Manual segmentation was performed by tracing the outer borders of the quadriceps muscle group in each axial slice using an interactive display and Medical Image Processing, Analysis, and Visualization (MIPAV) software. A single author who performed all tracings (C.K.) was blinded to subject identity. Muscle volume was calculated using statistical algorithms in MIPAV. This technique has been previously established as both reproducible and reliable.(Segal et al., 2014)

### Testing of Quadriceps Muscle Strength, Activation, and RTD

This methodology has been described at length in a previous publication.(see Chapter 2) Briefly, subjects were seated on the chair of an individually scaled FDA approved Testing & Rehabilitation System (HUMAC NORM, Computer Sports Medicine, Inc., Stoughton, MA) with consistent hip and knee angles of 85 and 90 degrees (Figure 2.1). The uninvolved leg was always tested first. Testing order, consistent between sessions, was: contractile properties, voluntary strength and RTD, followed by activation testing. Surface EMG electrodes (model 544, Therapeutics Unlimited, Iowa City, IA) were applied over the muscle bellies of the vastus lateralis (VL), rectus femoris (RF), and vastus medialis (VM).

Electrical stimulation was delivered to the quadriceps musculature using an FDA approved constant current stimulator (Digitimer Ltd., Model DS7AH, Hertfordshire, England).

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Subject-specific stimulus intensity was determined and the current producing peak torque was utilized for the contractile properties and voluntary activation (VA) tests.

Doublets were evoked at rest (current: 110% of the intensity required for peak twitch torque, 1 ms, 100 Hz, 400 V). Subjects completed 3 sets of doublets with 10 seconds of rest between stimulations.

For voluntary knee extensor efforts, subjects performed warm-up repetitions followed by a minimum of two maximal voluntary isometric knee extension ramp contractions to reliably determine peak voluntary knee extensor torque. Subjects were instructed to kick out as hard as possible. Loud verbal encouragement was provided to facilitate maximal torque production. After peak torque (MVIC) was reliably identified, subjects were instructed in the performance of rapid voluntary isometric (RTD) contractions. Subjects were specifically instructed to kick out as fast and as hard as possible, in an attempt to reach maximal torque production as quickly as possible.(Holtermann et al., 2007b, Sahaly et al., 2001, Bemben et al., 1990) Subjects completed five trials separated by 30 seconds of rest. To constitute a valid repetition, peak torque was required to reach 80% of the isometric peak torque established during MVIC efforts and no countermovement prior to contraction was allowed.

Following RTD testing, VA was assessed utilizing the interpolated twitch technique (ITT).(Krishnan and Williams, 2010) A stimulus superimposed on a maximal voluntary effort was triggered when the torque value reached a threshold based on a previously established cutoff.(Krishnan et al., 2009) A second stimulus of equal intensity was delivered shortly after the subject returned to rest in order to assess the muscle in its potentiated state. Subjects completed a minimum of two ITT trials. Additional trials were performed if VA varied by greater than 5% between trials.

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## Signal Sampling and Processing

### *Leg Press 1RM, Power, and Acceleration*

Power and Acceleration data was sampled at 400 Hz. LP strength (LP 1RM), peak power and peak acceleration (average of the best 3 out of 5 efforts) at 40% and 70% of 1RM were computed ($PP_{40}$, $PP_{70}$, $PA_{40}$, and $PA_{70}$) and normalized to body weight (kg). Peak acceleration was also normalized to the resistance on each repetition.

### *Torque and EMG Signals*

Torque signals were sampled at 2000 Hz with a 16-bit A-to-D PowerLab data acquisition system (Model ML880, ADInstruments, Inc., Colorado Springs, CO). HUMAC NORM signals were converted to torque values using previously validated conversion factors. EMG signals were sampled at 2000 Hz (Model 544, Therapeutics Unlimited, Iowa City, IA) with a cutoff frequency of 20 Hz. Custom software developed in LabChart v 7.3.7 (ADInstruments, Inc., Colorado Springs, CO) was utilized to record and store torque and EMG signals.

### *RTD from Voluntary Contractions*

Sampling of RTD and EMG signals was described at length in Chapter 2. Voluntary RTD torque signals were processed with custom algorithms created using Python programming language (Python Software Foundation, Beaverton, OR). Maximum rate of torque development (MRTD) was defined as the single data point at which the greatest positive slope (Nm/s) of the torque signal occurred. Torque time integrals (TTI) were computed from onset of torque development to 50, 100, and 200 ms.

### *EMG Signals from Voluntary RTD Contractions*

Quadriceps EMG signals were processed with custom Python programming algorithms. Root mean square (RMS) amplitude of EMG signals, computed from onset of contraction to discrete time points to align with torque data (e.g. $RMS_{0\text{-}50}$ for RMS value from EMG onset to 50

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ms), was calculated for the each muscle and normalized to RMS EMG amplitude obtained during ramp MVIC contractions. RMS value in a 500 ms window centered at peak torque was calculated for each ramp MVIC matched to RTD contraction by leg and interval. The normalized RMS values for VL, RF, and VM were averaged to create a mean quadriceps RMS EMG value for each interval. The automated method utilized for detecting EMG signal onset was previously validated and described in detail previously. (see Appendix)

### Data Analysis

IBM SPSS version 21.0 (IBM Corporation, Armonk, NY) was utilized for all statistical analyses. Descriptive statistics were calculated for each variable. Nonparametric statistics were used to test for significant differences by side and over time (due to small sample size and the distribution of key variables). Side by side asymmetries at each interval were evaluated using the Wilcoxon Signed-Ranks. Friedman's ANOVA followed by post hoc testing with a Bonferroni correction was performed to evaluate changes in RTD and power variables in the involved leg over time. Friedman’s ANOVA followed by post-hoc pairwise testing was also utilized to compare percentage deficits in LP and knee extensor strength, power, and RTD. A Spearman’s rank-order correlation was performed to evaluate the relationships between quadriceps muscle performance, lower extremity power, and subjective knee function. A significance level of $\alpha = .05$ was used for all analyses.

## Results

### Subjects

Each subject underwent APM performed by one of five fellowship trained University of Iowa Sports Medicine surgeons. Subjects had surgery an average of 4.5 ± 3.0 months following initial onset of symptoms. Four subjects had experienced previous arthroscopic knee procedures.

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One subject had a previous anterior cruciate ligament reconstruction with concomitant medial meniscus repair while three subjects underwent previous APM. Subjects completed the Pre Test session an average of 5.2 ± 4.1 days prior to surgery, the initial (2 week) post-test session 15.8 ± 3.3 days post-surgery, and the final (5 week) test session 36.9 ± 7.4 days post-surgery.

### Closed Chain Lower Extremity Strength & Power

The lower extremity strength and power results for each limb are summarized in Table 3.1. Significant differences were observed by side for all lower extremity strength and power variables. Strength, power, and acceleration generated by the involved leg were significantly lower than strength, power, and acceleration of the uninvolved leg at each interval. Deficits in power and acceleration were greater than deficits in strength, though only the differences between $PP_{40}$ and 1RM at 2 weeks post-surgery and $PA_{40}$ and 1RM at 5 weeks post-surgery reached statistical significance (Table 3.1 and Figure 3.2).

LP 1RM of the involved leg was significantly different between the pre-test and 5 week post-test for both the involved ($p = .029$) and uninvolved limbs ($p = .014$). There was a significant pairwise difference in involved leg $PP_{40}$ between the 2 week and 5 week intervals ($p = .014$) and in uninvolved leg $PA_{40}$ between the pre-test and 5 week post-test ($p = .014$) (Table 3.1).

### Quadriceps Muscle Volume, Strength, and RTD

Quadriceps muscle volume was lower in the involved limb at each interval, but the difference was only statistically significant at 2 weeks post-surgery ($p = .038$). Knee extensor MVIC and RTD were lower in the involved limb at all intervals, although pre-surgery MRTD and $TTI_{50}$ and 5 week post-surgery $TTI_{50}$ did not reach statistical significance. All side-to-side asymmetries in knee extensor strength and RTD were significantly different at 2 weeks post-

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surgery (Figure 3.3). At 2 weeks post-surgery, $TTI_{50}$ limb asymmetry was significantly different than MVIC asymmetry ($p = .028$). All other RTD deficits were greater than deficits in MVIC, but were not statistically significant. Involved leg RTD variables were lower at 2 weeks and 5 weeks post-surgery than pre-surgery, but these differences were not statistically significant. Knee extensor MVIC was significantly greater at 5 weeks post-surgery than pre-surgery in both limbs (Involved: $p = .029$; Uninvolved: $p = .04$).

Evoked doublet MRTD, normalized to peak evoked torque, was not significantly different between the involved and uninvolved limbs at any time period. The ratio of normalized voluntary to evoked MRTD was significantly greater in the uninvolved limb at 2 weeks ($p = .008$) and 5 weeks ($p = .05$) post-surgery. Quadriceps VA was significantly lower in the involved limb prior to surgery (Involved: 85.8%, Uninvolved: 91.5%), but there were no differences in VA following surgery (Figure 3.4).

Quadriceps RMS EMG was significantly lower at 2 weeks post-surgery in the involved limb. There were no significant differences preoperatively or at 5 weeks post-surgery, though EMG in both limbs was lower than pre-surgery values (Figure 3.5).

### Relationships between Lower Extremity Strength, Power, Acceleration and Quadriceps Muscle Performance and EMG Variables

Side-to-side limb asymmetries in isometric knee extensor RTD variables were greater than side-to-side asymmetries in lower extremity power and acceleration at 2 weeks post-surgery. There were significant differences between $TTI_{50}$ and LP 1RM ($p = .028$) and $TTI_{200}$ and LP 1RM ($p = .038$) deficits at 2 weeks post-surgery. In addition, there was a significant difference between the side-to-side deficit in $TTI_{50}$ and $PP_{40}$ at 2 weeks post-surgery ($p = .038$).

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Correlations between involved leg LP 1RM and PP/PA were stronger than correlations with any knee extensor strength or RTD variables, demonstrating task specificity. Involved leg $TTI_{200}$ was generally strongly positively correlated with PP and PA at all intervals, but not with LP 1RM. $TTI_{50}$ did not correlate with any closed chain LP variables (Table 3.2).

There were strong positive correlations between changes in knee extensor MVIC and LP PP/PA from pre-surgery to 5 weeks post-surgery. Changes in MRTD and $TTI_{200}$ were strongly positively correlated with changes in LP $PP_{40}$ and $PA_{40}$. Changes in LP 1RM were not significantly correlated with changes in any other strength, power, or RTD variable (Table 3.3).

### Subjective Knee Function

KOOS4 scores averaged 56.5 pre-surgery, 64.4 at 2 weeks post-surgery, and 78.7 at 5 weeks post-surgery. Side to side deficits in voluntary RTD variables were negatively correlated with KOOS scores pre-surgery and at 2 and 5 weeks post-surgery, though these correlations did not reach significance at 5 weeks post-surgery. KOOS scores and deficits in LE strength and power were, in general, weakly negatively correlated. KOOS scores and deficits in knee extensor MVIC were not correlated (Table 3.4).

WOMET-Total scores averaged 50.2 pre-surgery, 75.7 at 2 weeks post-surgery, and 86.0 at 5 weeks post-surgery. WOMET scores were not correlated with side to side deficits in knee extensor or lower extremity power variables. UCLA activity scores averaged 6.8 pre-surgery, 5.1 at 2 weeks post-surgery, and 7.1 at 5 weeks post-surgery, and were strongly negatively correlated with RTD deficits both prior to and following surgical intervention (Table 3.4).

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## Discussion

The importance of rapid muscle force development and muscle power to successful performance of typical daily activities and sports has been established in elderly patients and athletes.  However, the effect of injury or surgery on these muscle performance characteristics has not been well defined.  Theoretically, the period of relative inactivity following injury and/or surgery, coupled with the slow tempo of initial rehabilitation exercises, could significantly inhibit the ability to rapidly modulate muscle force and produce peak power, but there is limited evidence to support these concepts.

This investigation presents a novel perspective of the neuromuscular adaptations following knee arthroscopy that influence the ability to rapidly activate the quadriceps muscle and generate leg muscle power.  Significant side-to-side differences in LP power and knee extensor RTD are present after APM.  This is clinically relevant as APM patients often return to ambulation, work, and typical daily activities within 2 to 6 weeks of surgery.(Lubowitz et al., 2008, Umar, 1997)  This is a unique dataset which adds to our understanding of how people adapt following surgery and promotes scrutiny of the rehabilitation strategy (or lack thereof) for these patients.

Isometric knee extensor RTD deficits were greater than closed chain LP deficits at 2 weeks post-surgery.  Though knee surgery can affect all lower extremity muscles, quadriceps size, strength, and function is unequivocally altered by injury or surgery.(McLeod et al., 2012, Mizner et al., 2005, Schmitt et al., 2012, Williams et al., 2005a)  As assessed in this investigation, open chain knee extension isolates the quadriceps muscle, while a closed chain leg press movement may also include the contributions of the gastrocnemius/soleus, hamstrings, and gluteus muscles, and the input of these muscle groups can vary depending on resistance

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levels.(Da Silva et al., 2008) Greater deficits in isolated quadriceps function compared to closed chain leg extension indicate that subjects may utilize an alternate movement strategy to accomplish the task while partially compensating for quadriceps weakness. This effect was most prominent at 2 weeks post-surgery, coinciding with the period of significant deficits in rapid neural activation of the quadriceps. At 5 weeks post-surgery, side to side lower extremity power and acceleration asymmetries were similar in magnitude to RTD asymmetries and rapid neural activation was not significantly different by limb.

Despite the side to side asymmetries in closed chain LP measurements at 2 weeks post-surgery, involved leg normalized values at 5 weeks were greater than pre-test values (other than $PP_{70}$, which was 97% of pre-test value). This is in contrast to RTD variables, which for the most part were lower at 5 weeks post-surgery than pre-surgery (e.g. normalized MRTD was 86% of pre-test value). Thus, it seems that although the involved quadriceps got stronger, it also got slower. However, the involved leg did not become less powerful, and changes in involved leg MVIC were strongly correlated with changes in LP PP/PA (Table 3.3), suggesting that peak quadriceps strength is a more important factor in the ability to generate LP power than knee extensor RTD. In summary, increases in closed chain leg muscle power are correlated with increases in quadriceps strength, but improved leg muscle power is not associated with improvements in the ability to rapidly develop knee extensor torque.

Involved leg RTD $TTI_{200}$ was positively associated with involved leg PP and PA at all intervals. Although open chain isometric knee extension and closed chain leg press actions are fundamentally different activities, the results of this study indicate that open chain rapid knee extensor torque production is associated with closed chain LP power. In addition, improved knee extensor RTD was associated with improved closed chain LP power at lower levels of

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resistance. Despite the unique motor pattern of each activity, this data indicates that resolution of deficits in open chain quadriceps muscle performance may affect closed chain LP performance.

It is interesting to note that quadriceps volume was strongly positively correlated with LP 1RM, PP, and PA, but not correlated with RTD variables. In addition, later phase RTD variables (e.g., $TTI_{200}$) were more closely associated with LE power/acceleration than early phase RTD variables (e.g. $TTI_{50}$). This is not surprising as previous investigations have indicated that later phase RTD is more strongly correlated to quadriceps strength, while early phase RTD is strongly associated with rapid muscle activation.(Andersen et al., 2010, Tillin et al., 2012) The results of this study suggest deficits in isolated rapid quadriceps muscle performance, particularly at the initiation of contraction, do not affect LP power production, and therefore, would not be revealed in closed chain tests of LE muscle performance. This may obscure crucial information that can have significant functional consequences, as previous investigations have reported that the ability to rapidly develop quadriceps force at the initiation of contraction is a key determinant of functional ability (Brach et al., 2001, Clark et al., 2013, de Ruiter et al., 2006) and is strongly related to patient based outcomes.(Maffiuletti et al., 2010)

In clinical rehabilitation, closed chain exercises are often considered to be more “functional”, but this terminology lacks specificity and the theory is not properly justified, as closed chain measures of strength and power do not consistently correlate more closely with performance than open chain assessments. This could be due to test methodology (in equipment, instructions to subjects, data analysis, etc.), patient populations (untrained, experienced, etc.), or a plethora of other factors.

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It is important to obtain both measures of objective performance and patient based outcomes.(Mizner et al., 2005) Our data suggest that quadriceps RTD deficits are more strongly related to patient based outcomes than quadriceps strength or LP strength, power, or acceleration. Based on the concept that closed chain measurements are more functional, this may be a surprising result, but deficits in quadriceps muscle performance have been shown to be related to both poor/abnormal function and lower patient based outcomes scores. Quadriceps muscle performance, particularly rapid force development, may be the primary limiting factor in this population, and therefore could have the strongest relationship to function. RTD may be a more sensitive measure and a better indicator of overall "recovery" following injury/surgery.

Our results suggest the observed RTD and LP power deficits are related to neural factors. Particularly, the ability to rapidly recruit and drive the quadriceps muscle limits rapid force production in the early post-surgical period. This should not be confused with the ability to fully activate a muscle – voluntary activation failure was between 93% and 95% in both limbs at each post-surgical measurement.

This is the first published study to investigate lower extremity power, quadriceps muscle performance and patient based outcomes in a group of subjects undergoing arthroscopic knee surgery. The clinical relevance of this study and the potential for development in this area are significant. The majority of human activities, both in sports and daily tasks, are characterized by rapid muscle activation and relaxation. Quadriceps neuromuscular deficits are a hallmark of knee injury and/or surgery, but these deficits can be masked during multi-joint assessments of muscle performance. Our results indicate that sustained quadriceps neuromuscular deficits are strongly negatively correlated with patient based outcomes. The results of this study suggest that crafting interventions to safely resolve the deficits in rapid quadriceps activation/force

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production following knee injury and/or surgery would promote better normalization of neuromuscular function and could improve outcomes.

Future investigations will more thoroughly examine the neuromuscular mechanisms and clinical relevance of these concepts. Populations with greater neuromuscular deficits, such as those undergoing ACL reconstruction, will be evaluated. Interventions which target rapid muscle activation or retraining the system to be able to appropriately modulate force will be developed and tested. Improving rehabilitation strategies could result in earlier normalization of lower extremity biomechanics, neuromuscular function, and better long-term knee-related quality of life. This would be a very significant development.

The authors recognize the limitations of this work. Only surface EMG from open chain isometric knee extension was collected. Ideally, EMG collected from closed chain LP could be utilized to determine the potential contribution of various LE muscles to the LP task, and would indicate whether involved limb rapid quadriceps activation was normal or limited during closed chain LP performance.

An isokinetic dynamometer with stock lower leg attachments was utilized to perform isometric knee extension tests. A system with less compliance would be preferred for RTD analysis.(de Ruiter et al., 2004a) Pilot testing in our lab indicated that using a compliant system may inflate recorded torques during the early portion of RTD trials. This effect was noted only in the very early period of contraction (0-50 ms); thus, torque variables less than 50 ms were not analyzed in this data set. As all analyses were measures of comparison between limbs or collection periods, any influence of pad compliance on RTD measurements does not affect the results presented.

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It is important to note that no one measure of power or rapid force production has been shown to be most strongly related to function or most predictive of sports performance or successful completion of daily activities.(Cronin and Sleivert, 2005) As Cronin and Sleivert noted, although some evidence suggests stronger correlations between power and function than strength and function, the results of investigations comparing power and function also demonstrate variable results. More research is necessary to truly understand how rapid muscle activation and/or muscle power specifically contributes to successful performance of movement strategies or tasks required in sports or everyday life.

Subjects in this investigation were part of a larger randomized controlled trial examining various quadriceps training protocols following APM. However, there were no differences in RTD, LE power, or muscle activation between treatment groups. All subjects completed guided quadriceps exercises in the early post-operative period, and the possible effect of this treatment on the results presented in this paper is the mitigation of deficits in quadriceps muscle performance. Thus, the deficits presented in this report are likely to be more substantial in people who do not complete specific quadriceps training following APM.

## Conclusion

People undergoing APM have significant deficits in measures of rapid knee extensor torque development and lower extremity power. Deficits in isolated quadriceps strength and speed are greater than deficits in closed chain leg press strength and speed early after surgery and do not resolve as rapidly as closed chain deficits. The inability to quickly develop or modulate quadriceps force may have significant functional consequences. Clinicians should be cognizant of the scope of neuromuscular deficits following knee injury and surgery, and consider

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implementing treatment strategies to mitigate these deficits. This work has the potential to alter evaluation and rehabilitation practices and improve the treatment and rehabilitation of people suffering from musculoskeletal injury.

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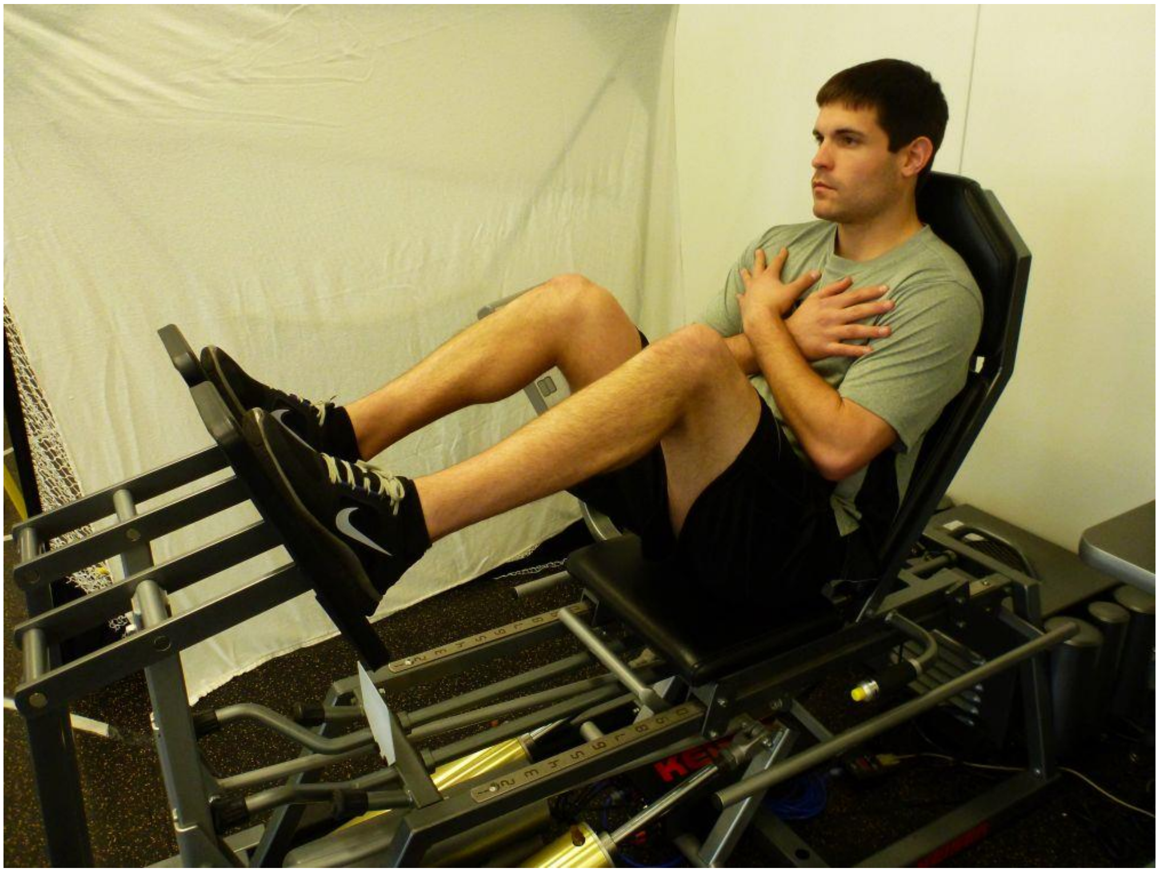

Figure 3.1: Subject positioned on Keiser A420 pneumatic instrumented leg press device for measuring lower extremity strength and power.

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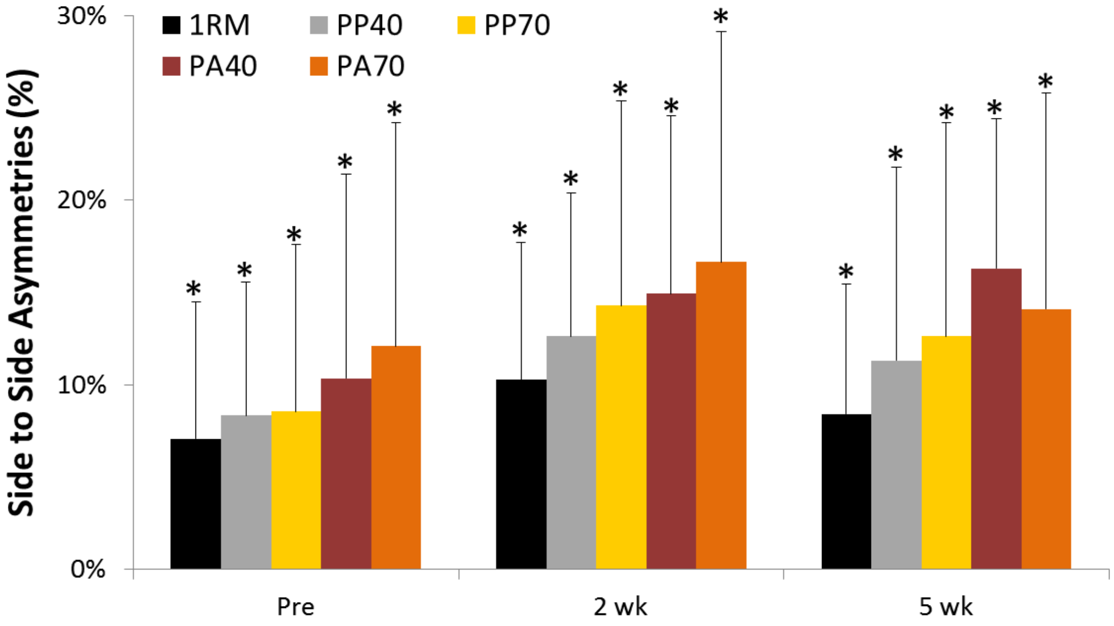

Figure 3.2: Mean side to side deficits in leg press strength (1RM), peak power, and peak acceleration at each interval. Power and acceleration were tested at 40% and 70% of 1RM.

**Abbreviations:** 1RM, one repetition maximum leg press strength; PP40, peak power at 40% 1RM resistance; PP70, peak power at 70% 1RM resistance; PA40, peak acceleration at 40% 1RM resistance; PA70, peak acceleration at 70% 1RM resistance.
* = significant difference between involved and uninvolved legs (p < .05).
Error bars are +1 SD.

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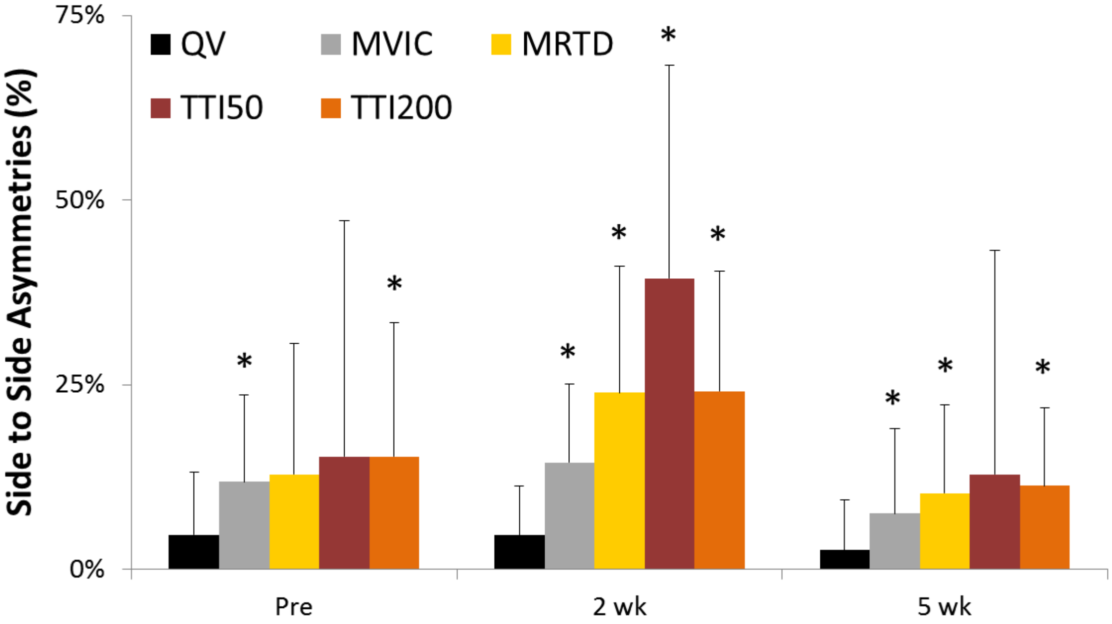

Figure 3.3: Mean side to side deficits in quadriceps volume, voluntary knee extensor strength & RTD variables.

**Abbreviations:** QV, quadriceps volume (cm3); MVIC, maximum voluntary isometric contraction; MRTD, maximum rate of torque development; TTI50, torque time integral from 0-50 ms; TTI200, torque time integral from 0-200 ms.

* = significant difference between involved and uninvolved legs ($p < .05$).

Error bars are +1 SD.

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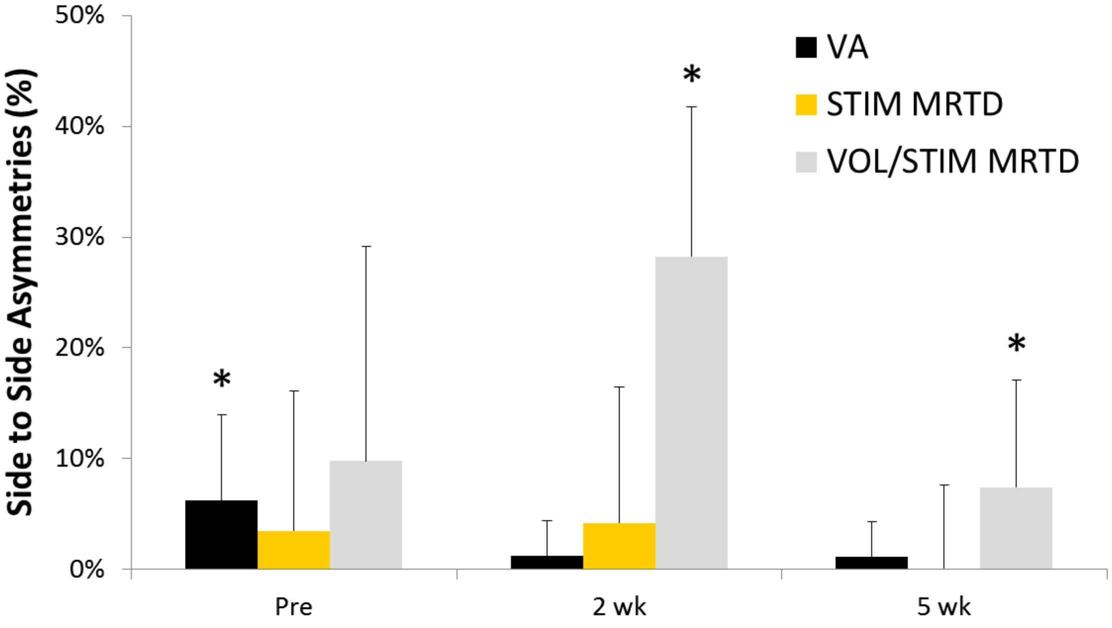

Figure 3.4: Mean side to side deficits in quadriceps voluntary activation and evoked MRTD. Evoked MRTD is normalized to peak evoked torque and voluntary MRTD is normalized to MVIC.

**Abbreviations:** VA, voluntary activation; STIM MRTD, evoked maximum rate of torque development; VOL/STIM MRTD, ratio of normalized voluntary maximum rate of torque development to normalized evoked maximum rate of torque development.

* = significant difference between involved and uninvolved legs ($p < .05$).

Error bars are +1 SD.

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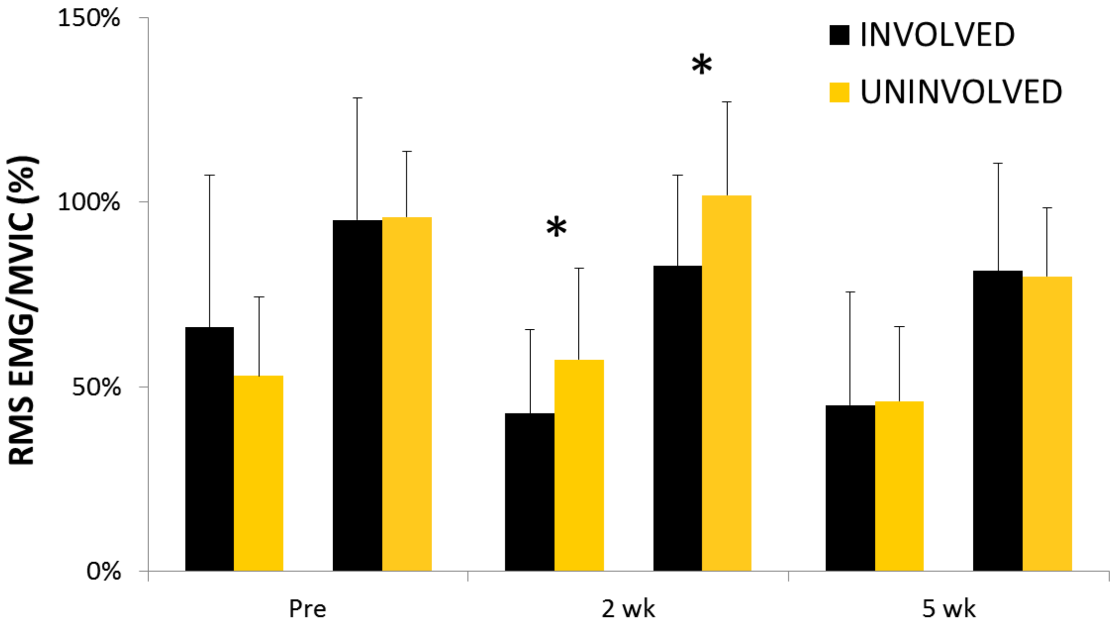

Figure 3.5: Mean quadriceps RMS EMG during voluntary knee extensor RTD trials from 0-50 ms and 0-200 ms at each interval with both legs. RMS Values are normalized to RMS EMG amplitude from ramp MVIC contractions.

**Abbreviations:** RMS EMG/MVIC (%), root mean square EMG from MRTD contractions normalized to root mean square EMG in a 500 ms window at peak torque production during MVIC trials.

* = significant difference between involved and uninvolved legs ($p < .05$).

Error bars are +1 SD.

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Table 3.1: Leg Press strength, power, and acceleration by leg prior to surgery and at 2 and 5 weeks post-surgery

| | **Pre Test** | | | | **2 wk post surgery** | | | | **5 wk post surgery** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Variable** | Involved | Uninvolved | Deficit | p Value | Involved | Uninvolved | Deficit | p Value | Involved | Uninvolved | Deficit | p Value |
| LP 1RM (N/kg) | 8.2 ± 1.3 | 8.8 ± 1.1 | 7.1% | ***0.012*** | 8.2 ± 1.2 | 9.1 ± 1.3 | 10.3% | ***0.012*** | *8.5 ± 1.3 | *9.3 ± 1.3 | 8.4% | ***0.018*** |
| PP$_{40}$ (W/kg) | 11.4 ± 2.5 | 12.4 ± 2.5 | 8.3% | ***0.008*** | 10.9 ± 2.3 | 12.4 ± 2.6 | $^{\$}$12.6% | ***0.008*** | $^{\#}$11.4 ± 2.4 | 12.9 ± 2.4 | 11.3% | ***0.021*** |
| PP$_{70}$ (W/kg) | 11.2 ± 2.8 | 12.2 ± 2.8 | 8.5% | ***0.021*** | 10.6 ± 2.3 | 12.4 ± 2.7 | 14.2% | ***0.021*** | 10.9 ± 2.4 | 12.5 ± 2.7 | 12.6% | ***0.021*** |
| PA$_{40}$ (G * N/kg) | 12.0 ± 4.1 | 13.4 ± 4.1 | 10.3% | ***0.008*** | 12.4 ± 3.7 | 14.5 ± 4.5 | 14.8% | ***0.011*** | 12.5 ± 3.7 | *14.9 ± 4.3 | $^{\$}$16.2% | ***0.008*** |
| PA$_{70}$ (G * N/kg) | 6.2 ± 2.2 | 7.0 ± 1.9 | 12.1% | ***0.011*** | 5.9 ± 1.7 | 7.0 ± 1.6 | 16.5% | ***0.011*** | 6.3 ± 1.9 | 7.3 ± 1.6 | 14.1% | ***0.015*** |

**Abbreviations:** LP 1RM, one repetition maximum leg press strength normalized to body mass (kg); PP$_{40}$, peak power at 40% 1RM resistance; PP$_{70}$, peak power at 70% 1RM resistance; PA$_{40}$, peak acceleration at 40% 1RM resistance; PA$_{70}$, peak acceleration at 70% 1RM resistance; W, watts; G, acceleration in units of gravity.

*significant differences between pre surgery value and 5 week post-surgery value ($p < .05$)

$^{\#}$significant difference between pre surgery value and 2 week post-surgery value ($p < .05$)

$^{\$}$significant difference between power or acceleration percentage deficit and 1RM percentage deficit at specified testing period ($p < .05$)

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Table 3.2: Correlations (Spearman's rs) between involved leg quadriceps volume, strength, RTD and leg press power/acceleration variables prior to surgery and at 2 and 5 weeks post-surgery

| | | QV | MVIC | MRTD | $TTI_{50}$ | $TTI_{200}$ | LP 1RM | $PP_{40}$ | $PP_{70}$ | $PA_{40}$ | $PA_{70}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| QV | Pre | - | | | | | | | | | |
| | 2 wk | - | | | | | | | | | |
| | 5 wk | - | | | | | | | | | |
| MVIC | Pre | .667* | - | | | | | | | | |
| | 2 wk | 0.600 | - | | | | | | | | |
| | 5 wk | 0.600 | - | | | | | | | | |
| MRTD | Pre | 0.350 | 0.633 | - | | | | | | | |
| | 2 wk | 0.283 | 0.567 | - | | | | | | | |
| | 5 wk | 0.450 | 0.400 | - | | | | | | | |
| $TTI_{50}$ | Pre | -0.083 | 0.383 | .833** | - | | | | | | |
| | 2 wk | -0.500 | 0.033 | 0.217 | - | | | | | | |
| | 5 wk | -0.133 | 0.150 | 0.650 | - | | | | | | |
| $TTI_{200}$ | Pre | 0.467 | .717* | .983** | .783* | - | | | | | |
| | 2 wk | 0.583 | .783* | .817** | 0.067 | - | | | | | |
| | 5 wk | 0.600 | .733* | .783* | 0.55 | - | | | | | |
| LP 1RM | Pre | .750* | .700* | 0.450 | 0.217 | 0.483 | - | | | | |
| | 2 wk | .700* | 0.383 | 0.183 | -0.700* | 0.317 | - | | | | |
| | 5 wk | 0.550 | 0.450 | 0.300 | 0.167 | 0.550 | - | | | | |
| $PP_{40}$ | Pre | .800** | .833** | .683* | 0.250 | .733* | .767* | - | | | |
| | 2 wk | .917** | 0.600 | 0.517 | -0.500 | .700* | .683* | - | | | |
| | 5 wk | .850** | 0.550 | 0.550 | 0.167 | .750* | .700* | - | | | |
| $PP_{70}$ | Pre | .867** | .667* | 0.450 | -0.017 | 0.533 | 0.65 | .917** | - | | |
| | 2 wk | .883** | 0.367 | 0.250 | -0.700* | 0.383 | .700* | .917** | - | | |
| | 5 wk | .933** | 0.400 | 0.350 | -0.183 | 0.483 | 0.633 | .883** | - | | |
| $PA_{40}$ | Pre | .767* | .783* | .733* | 0.333 | .767* | .783* | .983** | .900** | - | |
| | 2 wk | .867** | 0.533 | 0.550 | -0.533 | .667* | .667* | .983** | .933** | - | |
| | 5 wk | .833** | 0.500 | 0.600 | 0.183 | .733* | .683* | .983** | .850** | - | |
| $PA_{70}$ | Pre | .833** | .667* | .667* | 0.350 | .717* | .833** | .867** | .850** | .917** | - |
| | 2 wk | .917** | 0.600 | 0.517 | -0.500 | .700* | .683* | 1.000** | .917** | .983** | - |
| | 5 wk | .867** | 0.433 | 0.533 | 0.133 | .667* | .667* | .967** | .883** | .983** | - |

**Abbreviations:** QV, quadriceps volume ($cm^3$); MVIC, maximum voluntary isometric contraction; MRTD, maximum rate of torque development; $TTI_{50/200}$, torque time integral from 0-50/200 ms; LP 1RM, one repetition maximum leg press strength; $PP_{40/70}$, peak power at 40/70% 1RM resistance; $PA_{40/70}$, peak acceleration at 40/70% 1RM resistance.

*Correlation is significant at the 0.05 level (2-tailed)

**Correlation is significant at the 0.01 level (2-tailed)

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Table 3.3: Correlations (Spearman's rs) between changes in involved leg knee extensor strength/RTD and leg press power/acceleration from pre – 5 weeks post-surgery

| | MVIC | MRTD | $TTI_{50}$ | $TTI_{200}$ | LP 1RM | $PP_{40}$ | $PP_{70}$ | $PA_{40}$ | $PA_{70}$ |
|---|---|---|---|---|---|---|---|---|---|
| MVIC | - | | | | | | | | |
| MRTD | .879** | - | | | | | | | |
| $TTI_{50}$ | 0.377 | 0.483 | - | | | | | | |
| $TTI_{200}$ | .678* | .683* | .883** | - | | | | | |
| LP 1RM | 0.209 | 0.083 | 0.600 | 0.417 | - | | | | |
| $PP_{40}$ | .778* | .767* | 0.583 | .783* | 0.133 | - | | | |
| $PP_{70}$ | .753* | 0.633 | 0.400 | 0.600 | 0.117 | .900** | - | | |
| $PA_{40}$ | .753* | .700* | 0.167 | 0.400 | 0.200 | 0.650 | 0.550 | - | |
| $PA_{70}$ | 0.561 | 0.233 | 0.033 | 0.150 | 0.567 | 0.300 | 0.400 | .667* | - |

**Abbreviations:** MVIC, maximum voluntary isometric contraction; MRTD, maximum rate of torque development; $TTI_{50/200}$, torque time integral from 0-50/200 ms; LP 1RM, one repetition maximum leg press strength; $PP_{40/70}$, peak power at 40/70% 1RM resistance; $PA_{40/70}$, peak acceleration at 40/70% 1RM resistance.

*Correlation is significant at the 0.05 level (2-tailed)

**Correlation is significant at the 0.01 level (2-tailed)

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Table 3.4: Correlations (Spearman's rs) between outcomes scores and side-to-side asymmetries in quadriceps volume, strength and RTD variables at 2 and 5 weeks post-surgery

| **(A)** | **Pre surgery** | | | |
|---|---|---|---|---|
| | KOOS4 | | UCLA | |
| | $r_s$ | p value | $r_s$ | p value |
| MVIC | -0.317 | 0.406 | -0.498 | 0.173 |
| MRTD | -0.717 | ***0.030*** | -0.684 | ***0.042*** |
| $TTI_{200}$ | -0.400 | 0.286 | -0.321 | 0.400 |
| LP 1RM | -0.617 | 0.077 | -0.329 | 0.387 |
| $PP_{40}$ | -0.343 | 0.366 | -0.165 | 0.671 |
| $PP_{70}$ | -0.343 | 0.366 | -0.123 | 0.753 |

| **(B)** | **2 weeks post surgery** | | | |
|---|---|---|---|---|
| | KOOS4 | | UCLA | |
| | $r_s$ | p value | $r_s$ | p value |
| MVIC | -0.067 | 0.865 | -0.529 | 0.143 |
| MRTD | -0.683 | ***0.042*** | -0.468 | 0.204 |
| $TTI_{200}$ | -0.417 | 0.265 | -0.676 | ***0.046*** |
| LP 1RM | -0.183 | 0.637 | -0.199 | 0.607 |
| $PP_{40}$ | -0.293 | 0.444 | 0.035 | 0.929 |
| $PP_{70}$ | -0.267 | 0.488 | 0.069 | 0.859 |

| **(C)** | **5 weeks post surgery** | | | |
|---|---|---|---|---|
| | KOOS4 | | UCLA | |
| | $r_s$ | p value | $r_s$ | p value |
| MVIC | -0.017 | 0.966 | -0.380 | 0.314 |
| MRTD | -0.450 | 0.224 | -0.552 | 0.123 |
| $TTI_{200}$ | -0.533 | 0.139 | -0.690 | ***0.040*** |
| LP 1RM | 0.084 | 0.831 | -0.303 | 0.428 |
| $PP_{40}$ | -0.167 | 0.668 | -0.328 | 0.389 |
| $PP_{70}$ | -0.367 | 0.332 | -0.431 | 0.246 |

**Abbreviations:** MVIC, maximum voluntary isometric contraction; MRTD, maximum rate of torque development; $TTI_{200}$, torque time integral from 0-200 ms; LP 1RM, one repetition maximum leg press strength; $PP_{40/70}$, peak power at 40/70% 1RM resistance.

**Note:** Knee Extensor strength and RTD variables are highlighted in gold, LP strength and power variables are highlighted in orange

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# CHAPTER 4

# PERFORMING FASTER QUADRICEPS CONTRACTIONS IN REHABILITATION AFTER ARTHROSCOPIC PARTIAL MENISCECTOMY IS ASSOCIATED WITH GREATER RAPID TORQUE DEVELOPMENT CAPACITY AND BETTER PATIENT REPORTED OUTCOMES

## Introduction

There is a growing body of evidence which indicates that people who undergo arthroscopic knee surgery have significant deficits in the ability to rapidly activate the quadriceps muscle and rapidly produce quadriceps force following surgery.(Angelozzi et al., 2012, Cobian et al., 2015a, Cobian et al., 2015b, Jordan et al., 2014, Knezevic et al., 2014, Larsen et al., 2015, Maffiuletti et al., 2010, Winters et al., 2013) These deficits may be greater than deficits in the ability to develop peak force (Knezevic et al., 2014, Maffiuletti et al., 2010), and can persist after strength insufficiencies have been resolved.(Angelozzi et al., 2012) In these populations, deficits in rapid quadriceps force development may be more closely related to function than deficits in peak force generation.(Maffiuletti et al., 2010) Additional investigations have shown that significant deficits in lower extremity power production persist for years after surgery and after people have returned to sport or typical activities.(Neeter et al., 2006, Thomee et al., 2012)

Despite this body of evidence, quadriceps setting and straight leg raise exercises performed with slow ramp or ramp-and-hold style contractions are ubiquitous in the initial phase of rehabilitation protocols for the majority of arthroscopic knee procedures.(Kozlowski et al., 2012, Meier et al., 2008, O'Connor and Jackson, 2001, Shaw et al., 2005, Wilk et al., 2012) Patients are often instructed to focus on control of movement, which translates to low intensity actions with gradual rise in and relaxation of muscle activation. Rapid contractions or power

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training are not typically introduced until months after surgery.(Kozlowski et al., 2012, Wilk et al., 2012)

In rehabilitation settings, exercise dosage is focused on sets, repetitions, and resistance. Exercise tempo is rarely well controlled or specifically dosed.(Feigenbaum and Pollock, 1999) Neuromuscular adaptations are specific to the training stimulus - the response to an exercise protocol performed with slow controlled efforts compared to rapid explosive efforts is markedly different.(Maffiuletti and Martin, 2001, Neils et al., 2005, Tillin and Folland, 2014) In the fields of strength & conditioning and sports performance, power and speed training are commonly prescribed interventions to enhance an athlete's ability to rapidly generate force and maximize jump height, sprinting speed, and agility for more effective performance of sports specific activities.(American College of Sports, 2009, Cormie et al., 2011, Cronin et al., 2001, Cronin and Hansen, 2005, Haff, 2012, Lorenz et al., 2013) Elderly individuals have demonstrated strong positive responses to power training interventions, improving balance and functional ability.(Bottaro et al., 2007, Miszko et al., 2003, Orr et al., 2006, Tschopp et al., 2011) Despite these findings, proper or specific dosage of exercise tempo for individuals undergoing surgery and subsequent rehabilitation is largely ignored.

Previous investigations from our laboratory have illustrated the deficits in power, rapid muscle activation, and rapid torque development in a group of individuals undergoing arthroscopic partial meniscectomy (APM).(Cobian et al., 2015a, Cobian et al., 2015b) Following surgery, the subjects in this group completed training interventions with a goal of maximizing strength and volume of the quadriceps musculature. The purpose of this investigation was to analyze isometric knee extension training data for this group of subjects and evaluate the

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relationships between self-selected rate of torque increase and muscle activation during training and changes in the ability to rapidly produce torque, along with post-surgical outcomes.

The hypotheses of this investigation were:

1) Patients who trained with faster knee extensor rate of torque development (RTD) following APM would be able to produce greater maximal RTD at the post-training test session
2) Patients who trained with faster knee extensor RTD following APM would have better patient-based outcomes scores following training
3) Changes in quadriceps muscle strength and volume would be associated with normalized torque integrals but not with training RTD following APM

## Methods

### Subjects

15 right leg dominant people (8 males, 7 females, age 39.9 ± 14.8, BMI 26.5 ± 3.1) agreed to participate in this study. All subjects underwent APM performed by one of five University of Iowa surgeon investigators. Subjects with concomitant knee ligament injury or recent fracture, quadriceps muscle rupture, history of neurological disorder, BMI > 40, or additional medical conditions were excluded. Subjects completed a basic lower extremity physical examination prior to completing enrollment. A comprehensive description of the study procedures was provided to each subject prior to obtaining consent. This investigation was approved by the University of Iowa Human Subjects Research Institutional Review Board. Subjects in this study were part of a larger randomized controlled trial investigating the neuromuscular effects of surgery and early rehabilitation following APM.

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### Testing Procedures

Subjects completed a battery of tests and measures before surgery and approximately 2 weeks and 5 weeks after surgery with each leg. Tests were carried out in a consistent order at each interval. A brief review of the methodology of this investigation will be provided here, as the tests and measures have previously been described in detail (see Chapter 2).

### Quadriceps Muscle Volume

Axial T1-weighted images of quadriceps muscle volume (Siemens Medical Solutions USA, Inc., Malvern, PA) were acquired with a Siemens TIM Trio 3T scanner. A previously established technique was utilized to define and calculate quadriceps muscle volumes (QV).(Segal et al., 2014)

### Patient-Based Outcomes

Subjects completed the KOOS, WOMET, and UCLA activity score, instruments shown to be valid and reliable for assessing patient-reported outcomes in this population.(Naal et al., 2009, Roos and Lohmander, 2003, Sihvonen et al., 2012) The KOOS4 composite score and WOMET Total score were used in the final analysis. In addition, pain level was assessed at each test session using a visual analog scale (VAS).(Flandry et al., 1991)

### Testing of Quadriceps Muscle Contractile Properties, Strength, Activation, and RTD

An FDA approved Testing & Rehabilitation System (HUMAC NORM, Computer Sports Medicine, Inc., Stoughton, MA) was utilized for assessing quadriceps neuromuscular performance. Subjects were positioned in the chair of the testing device with hip and knee angles of 85 and 90 degrees, respectively. The leg testing adapter pad was secured to the shank approximately 5 cm proximal to the medial malleolus. Custom adjustments were made for each

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subject to align the dynamometer center with the knee joint axis of rotation. These custom alignments were recorded and applied at each subsequent data collection (Figure 4.1).

Subjects completed warm-up repetitions followed by maximal voluntary isometric knee extension ramp contractions (MVIC). Subjects were directed to kick out as hard as possible and loud verbal encouragement was provided to facilitate maximal torque production. Following MVIC efforts, subjects were instructed in performance of rapid voluntary isometric contractions, utilized to assess the maximal RTD of the knee extensors. To complete this task, subjects were specifically directed to kick out as fast and as hard as possible.(Holtermann et al., 2007b, Sahaly et al., 2001, Bemben et al., 1990)

### Rehabilitation Programs

Subjects in this study completed rehabilitation sessions 2-3 times per week, beginning two days following surgery. All subjects performed 10 second maximal voluntary ramp isometric quadriceps contractions. During the first three training sessions, subjects completed 10 high intensity MVICs. The exercise volume was doubled after the third session and subjects completed 20 repetitions per session for the remainder of the training period (sessions 4 – 10). Following the fifth rehabilitation session, subjects again completed all pre-surgical tests and measures (2 week post-test session), a process repeated following the tenth and final rehabilitation session (5 week post-test session) (Table 4.1).

To perform quadriceps exercise, subjects were seated in the chair of a Humac NORM Testing & Rehabilitation System, in the identical position as the testing procedures, with the knee positioned in 90° of flexion (Figure 4.1). Skin preparation was completed and surface EMG electrodes (model SX230-1000, Biometrics Ltd, Ladysmith, VA) were secured over the muscle bellies of the vastus medialis (VM) and vastus lateralis (VL). Subjects performed

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warmup isometric knee extension repetitions with the uninvolved leg first, followed by warmup repetitions of increasing effort with the involved leg. Real-time visual feedback of knee extension torque production was provided. The Humac NORM testing software was formatted to guide the timing of isometric contractions and rest periods.

Subjects were instructed to kick out as hard as they could and continue to maintain a maximal effort isometric knee extension contraction for 10 seconds. Subjects were provided with strong verbal encouragement to maximize torque production during each effort and instructed to breathe out as they performed each knee extension repetition. Subjects were not provided with any guidelines regarding the tempo of kicking out or relaxing. Each repetition was separated by 30 seconds of rest.

Eight of the subjects in this study performed high intensity voluntary exercise only (HI). The other seven subjects also completed the identical high intensity voluntary exercise protocol, but in addition received concurrent neuromuscular electrical stimulation (NMES). NMES was delivered using a portable stimulator (Compex3, Compex Medical SA, Ecublens, Switzerland) and two 2.5” x 5” self-adhesive muscle stimulation electrodes (UltraStim Electrodes, Axelgaard Manufacturing Co., Fallbrook, CA) placed at the proximal and distal portions of the quadriceps muscles. A symmetric, biphasic, square waveform (100 Hz, 400 μs pulse duration, 1-second ramp up, 9 seconds on) was delivered in tandem with voluntary knee extension efforts. Stimulation intensity was set at the subjects’ maximal tolerable level (Lyons et al., 2005), and subjects were encouraged to increase stimulation intensity as tolerated. During training sessions, subjects in the high intensity voluntary exercise + NMES (HI + NMES) group were instructed to initiate each voluntary knee extension contraction 3 seconds prior to the onset of NMES. Thus,

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torque production had leveled off by the time the stimulation began, and the use of NMES did not affect the rate of rise in voluntary torque production.

### Signal Sampling and Processing

#### *Testing Sessions*

Torque signals were sampled at 2000 Hz with a 16-bit A-to-D PowerLab data acquisition system (Model ML880, ADInstruments, Inc., Colorado Springs, CO). Signals from the HUMAC NORM were converted to torque values using previously validated conversion factors. Custom software developed in LabChart v 7.3.7 (ADInstruments, Inc., Colorado Springs, CO) was utilized to record and store torque signals. The signals collected from voluntary RTD trials were processed with custom algorithms created using Python programming language (Python Software Foundation, Beaverton, OR). The slope of the torque signal from 20% of peak torque to 80% of peak torque ($RTD_{TEST}$) was determined, which may be the period of torque rise most representative of the speed properties of the muscle.(Dudley-Javoroski et al., 2008)

#### *Training Sessions*

Torque and EMG signals from training sessions were sampled at 1000 Hz, again using the PowerLab data acquisition system and LabChart software. RTD from 20% of peak torque to 80% of peak torque was calculated from each training repetition and normalized to peak torque ($RTD_{TRAIN}$) (Figure 4.2). As training contractions did not involve maximal effort RTD, this variable was found to be the most reliable characterization of the rate of rise in torque production during the training repetitions and best discriminated between groups of subjects who trained with more rapid or more gradual RTD.

Torque integrals ($TI_{TRAIN}$) were calculated for each repetition and normalized to MVIC reached at that training session. Limb Symmetry Index ($LSI_{TRAIN}$) was also calculated for each

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training session ((MVIC Involved/MVIC Uninvolved) * 100) (Figure 4.2). These variables provided a representation of training intensity.

EMG training data was processed by applying a moving root mean square (RMS) filter with a 250 ms window length. The slope of the processed signal from onset of contraction to the greatest absolute value within the first second of data was computed for each repetition. This value was normalized to the greatest RMS EMG amplitude in a 500 ms window centered at peak torque reached during that training session. VL and VM data were averaged to create a single EMG variable ($EMG_{RR}$) representing the rate of EMG rise for each repetition (Figure 4.3).

Box plots were constructed of torque and EMG variables for each subject and extreme outliers (values > 3rd quartile + 3*interquartile range or < 1st quartile – 3*interquartile range) were excluded. Both torque and EMG variables from training sessions were averaged over all repetitions to create a grand mean of $RTD_{TRAIN}$ and $EMG_{RR}$ for each subject. $RTD_{TRAIN1-5}$ and $RTD_{TRAIN6-10}$ were also computed to determine if subjects trained with different speeds prior to and following the 2 week post-surgical test. $RTD_{TRAIN}$ / $RTD_{TEST}$ was calculated to determine what percentage of maximal possible RTD subjects trained with.

*Training RTD Groups*

Using $RTD_{TRAIN}$ data, subjects were divided into three tertiles based on $RTD_{TRAIN}$ values, each comprised of five subjects. The five subjects with the greatest $RTD_{TRAIN}$ values comprised the $RTD_{FAST}$ group while the $RTD_{SLOW}$ group consisted of the five subjects with the lowest $RTD_{TRAIN}$ values (Figure 4.4). A similar analysis was performed with $EMG_{RR}$ data, creating $EMG_{FAST}$ and $EMG_{SLOW}$ groups.

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### Data Analysis

All statistical analyses were performed using IBM SPSS version 21.0 (IBM Corporation, Armonk, NY). Descriptive statistics were calculated for each variable. 95% confidence intervals were calculated for $RTD_{TRAIN}$. Nonparametric statistics were utilized to perform tests of significance and correlational analysis based on the distribution of the data (the assumption of normality related to the primary outcome variables, assessed by Shapiro-Wilk's test, was violated). The Mann-Whitney U test was used to evaluate differences in RTD variables and outcomes between subjects in the $RTD_{FAST}$ and $RTD_{SLOW}$ tertiles. Spearman's correlation was performed to evaluate the associations between $RTD_{TRAIN}$, $TI_{TRAIN,}$ $LSI_{TRAIN}$, QV, strength, $RTD_{TEST}$, and subjective knee function. A single Wilcoxon signed-ranks test (Bonferroni correction) was performed to determine if subjects trained with different $RTD_{TRAIN}$ between early post-surgical and late post-surgical rehabilitation sessions. A significance level of $\alpha = .05$ was used for all analyses.

## Results

### Subjects

All subjects underwent partial meniscectomy performed by one of five fellowship trained University of Iowa Sports Medicine surgeons. There was a mean of 4.5 ± 3.1 months (range 0.5 -11 months) between onset of symptoms and date of surgery. Subjects completed the pre-test session an average of 4.4 ± 3.4 days prior to surgery, the initial (2 week) post-test session 15.9 ± 2.6 days post-surgery, and the final (5 week) test session 35.3 ± 6.3 days post-surgery.

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### Training RTD

All subjects were able complete all ten training sessions without issue, totaling 170 isometric knee extension repetitions per subject.  Due to software errors, data was not obtained from a total of eight repetitions (<<1% of all repetitions).  No trials were excluded as outliers based on $RTD_{TRAIN}$.  No subjects recorded mean $RTD_{TRAIN}$ greater than 50% of maximum capacity reached during testing sessions.  $RTD_{TRAIN}$ / $RTD_{TEST}$ varied from 14.2% to 45.4% (Table 4.2).  Coefficient of variation for $RTD_{TRAIN}$ averaged 30.7%, with a range of 15.6 to 39.9%.  $RTD_{TRAIN}$ was not significantly different between the first five training sessions and the final five training sessions (Wilcoxon signed-ranks test, p = .427).  There were no differences in $RTD_{TRAIN}$, pre or post-rehab $RTD_{TEST}$, UCLA activity score, KOOS4or WOMET Total scores between the HI and HI + NMES training groups.

$RTD_{TRAIN}$ was significantly positively correlated with change in $RTD_{TEST}$ from pre-surgery to 5 weeks post-surgery ($r_s$ = .557, p = .031) (Table 4.3).  $RTD_{TRAIN}$ was not correlated with pre-surgery involved leg $RTD_{TEST}$ ($r_s$ = -.139, p = .621) or pre-surgery side-to-side $RTD_{TEST}$ asymmetry ($r_s$ = .089, p = .752).

$RTD_{TRAIN}$ was significantly negatively correlated with deficits in $RTD_{TEST}$ ($r_s$ = -.604, p = .017) at 5 weeks post-surgery.  In addition, $RTD_{TRAIN}$ averaged over the initial five training sessions was significantly negatively correlated with deficits in $RTD_{TEST}$ at 2 ($r_s$ = -.557, p = .031) weeks post-surgery.

$RTD_{TRAIN}$ was strongly positively correlated with KOOS4 scores 5 weeks post-surgery ($r_s$ = .657, p = .008), but not with KOOS4 scores pre-surgery ($r_s$ = .032, p = .909).  $RTD_{TRAIN}$ was also correlated with WOMET Total scores 5 weeks post-surgery ($r_s$ = .582, p = .023), but again not correlated with WOMET Total scores pre-surgery ($r_s$ =.104, p = .713) (Figure 4.5).

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Lastly, $RTD_{TRAIN}$ was strongly positively correlated with changes in KOOS4 scores from pre-surgery to 5 weeks post-surgery ($r_s$ = .589, p = .021), and positively correlated with WOMET Total scores from pre-surgery to 5 weeks post-surgery ($r_s$ = .414, p = .125), although WOMET correlations did not reach significance. Conversely, $TI_{TRAIN}$ was not correlated with changes KOOS4 or WOMET Total scores from pre-surgery to 5 weeks post-surgery (KOOS4: $r_s$ = .136, p = .630, WOMET: $r_s$ = .021, p = .940). In addition, $LSI_{TRAIN}$ was not correlated with change in KOOS4 ($r_s$ = .089, p = .752) or WOMET Total scores ($r_s$ = .161, p = .567) from pre-surgery to 5 weeks post-surgery.

The $RTD_{FAST}$ group had significantly greater $RTD_{TRAIN}$, positive change in KOOS4 scores from pre-surgery to 5 weeks post-surgery, and change in $RTD_{TEST}$ from pre to 5 weeks post-surgery (Table 4.4) than the $RTD_{SLOW}$ group. Conversely, there were no differences between the $RTD_{FAST}$ and $RTD_{SLOW}$ training groups in age, BMI, pre-surgery UCLA activity score, changes in MVIC, QV, days between surgery and 5 week post-test, or VAS from pre to 5 weeks post-surgery.

### Training EMG

Approximately 1.5% of VL EMG repetitions and 2.3% of VM EMG repetitions were excluded as outliers. Approximately half of these exclusions were due to errors in data collection (hardware or software). $EMG_{RR}$ was positively associated with $RTD_{TRAIN}$ / $RTD_{TEST}$ and these correlations were significant. Similarly, $EMG_{RR}$ was moderately positively associated with changes in KOOS4 and WOMET Total scores from pre to 5 weeks post-surgery. $EMG_{RR}$ was not correlated with changes in MVIC or QV from pre to 5 weeks post-surgery (Table 4.5). When organized into tertiles by $EMG_{RR}$, the $EMG_{FAST}$ group had significantly greater $EMG_{RR}$

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than the $\text{EMG}_{\text{SLOW}}$ group (p = .009). The $\text{EMG}_{\text{FAST}}$ group also had significantly greater gain in KOOS4 scores from pre-surgery to 5 weeks post-surgery than the $\text{EMG}_{\text{SLOW}}$ group (p =.028).

## Discussion

This novel investigation aimed to evaluate the self-selected rate of torque rise that subjects post-APM trained with during performance of knee extensor MVICs and the correlations between various training speeds and strength, QV, RTD, and outcomes following training.

The hypotheses of this investigation were largely supported. The results of this study indicate that people who trained with greater RTD following APM both improved RTD and had better outcomes following rehabilitation than those who trained with a slower rate of torque rise. There were no differences in pre-surgical RTD or outcomes between subjects who trained with greater RTD and those who trained with lower RTD. Thus, subjects that trained with greater RTD weren't subjects that had higher RTD, activity levels, or better self-reported function prior to surgery. Changes in quadriceps strength and volume were not associated with $\text{RTD}_{\text{TRAIN}}$ or $\text{TI}_{\text{TRAIN}}$.

As the only instructions subjects were provided during training was to "kick as hard as you can", there was a significant range in the training speed that subjects employed. This provides further evidence that specific instructions must be given in order to properly evaluate maximum voluntary RTD and that testing repetitions cannot only include instructions to kick hard.(Holtermann et al., 2007b, Sahaly et al., 2001) The fact that no subjects in this study trained with ≥ 50% of maximum RTD capacity demonstrates the potential for more substantial improvements in post-surgical RTD if subjects are encouraged to train with a more rapid rise in torque production. It would be expected that rapid RTD efforts closer to maximal voluntary

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RTD capacity would result in greater increases in the ability to rapidly develop force, which could improve outcomes beyond what was observed in the $\text{RTD}_{\text{FAST}}$ training group.

The effects of training with rapid force development (RFD) at the initiation of contraction have been previously investigated in healthy and/or untrained subjects. Subjects who completed 4 weeks of elbow flexor RFD training demonstrated a 25% increase in peak strength and 24% increase in peak RFD. The increase in RFD was accompanied by a concurrent increase in the amplitude of elbow flexor EMG signal during the initial 100 ms of the rapid flexion contractions.(Barry et al., 2005) In an investigation by Geertsen et al., 14 subjects completed 12 dorsiflexion RFD training sessions over 4 weeks.(Geertsen et al., 2008) RTD and MVIC of the dorsiflexors increased following training, along with evidence of increased reciprocal inhibition of the soleus motoneurons (as measured by soleus H reflex). Oliveira et al. reported increases in early phase RFD measurements following a 6 week knee extensor RFD training period, but no changes in peak or later phase RFD.(Oliveira et al., 2013) In a study by Rich et al., 10 subjects performed 5 sets of 10 brief MVICs 3 times per week over 8 weeks and increased MVIC and peak RFD.(Rich and Cafarelli, 2000) Tillin et al. reported significant changes in agonist EMG in the early period of a rapid voluntary contraction following 4 weeks of isometric knee extensor RFD training. These changes were associated with increases in force production. The authors concluded that enhanced agonist neural drive and maximal force production accounted for improved explosive voluntary force production in the early and late phases of the contraction, respectively.(Tillin et al., 2012)

Behm et al. demonstrated the importance of intended rather than actual movement velocity in inducing specific training adaptations.(Behm and Sale, 1993) 16 subjects performed unilateral ankle dorsiflexion contractions, three days/week over 16 weeks (five sets of 10

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contractions each session), of either isometric or high speed (300 deg/s) isokinetic dorsiflexion. All subjects performed both types of training, each with one limb. The velocity specific response to training was nearly identical in both legs.

These results further illustrate that the response to a training intervention will vary depending on how the subject performs the training exercises. Although exercise volume is typically controlled in rehabilitation studies, exercise tempo may not be. In addition, training data is rarely obtained so despite the best efforts to instruct and control training parameters, in the majority of investigations the specific training parameters are unknown. Thus, two similar protocols in terms of exercise volume (sets x repetitions x resistance) could have significantly different outcomes based on how subjects perform the training repetitions.

In 2002, Aagaard et al. published the results of a study in which untrained subjects completed 14 weeks/38 sessions of heavy resistance lower extremity strength training (loads between 3RM and 10RM).(Aagaard et al., 2002a) Subjects in this investigation demonstrated significant increases in knee extension strength, normalized rate of force development (RFD), and rate of EMG rise in the initial phases of muscle contraction. Eight years later, the same group of authors published another investigation of untrained subjects who completed the identical resistance training protocol.(Andersen et al., 2010) In contrast to the results of the initial study, the subjects in the later study demonstrated increases in knee extension strength but *decreases* in early phase RFD. Although the commonly controlled parameters of exercise dosage were nearly identical (sets, repetitions, resistance), the response to training (in terms of rapid force production) was significantly different. In the methods section of the second study, the authors noted that “Subjects were instructed to lift and lower the weight stack in a controlled manner to avoid injuries, i.e. performing the movements without sudden jerk or

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acceleration,"(Andersen et al., 2010) while in the earlier study, no directions were provided regarding exercise tempo. As the results of the current publication suggest, self-selected exercise tempo can vary considerably. The improved RFD and early phase muscle activation in the first study could be caused by faster exercise tempo of the subjects performing resistance exercises without specific instructions, a point the authors acknowledged in the discussion section of the 2010 article.(Andersen et al., 2010)

In this investigation, the goal of the training intervention was to maximize quadriceps strength and size. The training protocol was successful in improving both strength and quadriceps volume (MVIC increased by 16.5%, QV increased by 5.6%). Strength and QV were not related to $\mathrm{RTD_{TRAIN}}$, while strength gains were remarkably similar between those in the $\mathrm{RTD_{FAST}}$ and $\mathrm{RTD_{SLOW}}$ groups (approximately 20% in both groups). This is the logical outcome, as subjects completed each repetition with the goal to maximize torque production. Thus, changes in strength should be relatively similar across the group (considering individual variation in response to training based on previous training status, age, genetics, etc.).

However, subjects who trained with greater RTD improved strength and maintained a greater capacity for voluntary RTD. Thus, considering the RTD deficits in this population (Cobian et al., 2015b) and the potential functional importance of RTD, a training intervention that incorporates training with rapid muscle activation/force production in concert with maximal force production may be more advantageous. In a recent investigation, Tillin et al. randomized 19 subjects to an explosive strength training (EST) or maximal strength training (MST) group.(Tillin and Folland, 2014) Both groups completed 4 weeks of isometric knee extension contractions. The EST group contracted as fast and as hard as possible for one second, while the MST group performed a one second ramp contraction and three second hold prior to relaxing.

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Maximal force production increased 11% in the EST group and 21% in the MST group. Normalized rapid force production increased 53% in the EST group and decreased 14% in the MST group. Quadriceps EMG at maximal force production increased significantly in the MST group but not in the EST group. Conversely, initial quadriceps EMG increased significantly in the EST group but not in the MST group. These distinct neuromuscular adaptations were specific to the training stimulus. By combining these two approaches – rapid activation/RFD followed by greater time under tension with a significant load – we may be able to induce improvements in both strength and RTD/RFD, more specifically addressing the deficits people present with following knee surgery and maximizing neuromuscular performance and functional outcomes.

Selvanayagam and colleagues evaluated the neural responses following a single session of isometric strength training, performed either with slow ramp contractions, ballistic contractions with a 2 second hold at maximal force, or ballistic contractions with immediate relaxation after the initial effort.(Selvanayagam et al., 2011) The authors found that a single session of any of the three types of training produced evidence of a shift in transcranial magnetic stimulation-induced twitch force direction toward the training direction. They also concluded that the strongest early neural effects were observed from the ballistic contractions with a 2 second MVIC hold, combining ballistic and maximum force generation.

Conversely, the self-selected differences in training RTD may be due to the differences in outcomes and functional status following surgery. As training RTD was self-selected, only the associations between $\text{RTD}_{\text{TRAIN}}$ and outcomes can be computed, without any inference regarding the direction of this relationship. Thus, it may not be that training with a faster rate of torque rise improves outcomes, but rather that improved outcomes result in a greater knee extensor RTD

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when training. Depending on the direction of this relationship, $\text{RTD}_{\text{TRAIN}}$ may either be a training parameter than can be manipulated to improve outcomes, or a marker of recovery following APM. Future investigations should utilize randomized controlled trials which can assess the directional status of the relationships between knee extensor training RTD, patient-based outcomes, and maximal RTD.

The authors recognize the limitations of this study. The variation in training RTD within subjects is substantial (coefficient of variation averaged 31%). However, it was expected that there would be significant variation in RTD between repetitions performed without any direction or regulation of the rate of rise in torque production. Despite the inter-individual variations, there was a large and significant difference in $\text{RTD}_{\text{TRAIN}}$ between the $\text{RTD}_{\text{FAST}}$ and $\text{RTD}_{\text{SLOW}}$ groups – the fast group trained at an average of 39.5% of $\text{RTD}_{\text{TEST}}$ while the slow group trained at an average of 16.7% of $\text{RTD}_{\text{TEST}}$ ($p = .009$). Isometric strength training may have limited benefits beyond the joint angles and tasks performed in training. However, significant deficits in the ability to rapidly activate the quadriceps muscle following knee injury and/or surgery (Angelozzi et al., 2012, Cobian et al., 2015b, Jordan et al., 2014, Maffiuletti et al., 2010) may be negatively affecting the performance of typical daily and sports activities, many which require rapid development of quadriceps force.(Aagaard et al., 2002a, Cappellini et al., 2006, Gazendam and Hof, 2007, Rand and Ohtsuki, 2000) If so, we would expect functional improvements with the resolution of these deficits. Lastly, this investigation features a relatively small sample size. Although the majority of the relationships analyzed reached statistical significance, it is important to be cautious about making wide ranging conclusions from this investigation.

Future studies should utilize randomized controlled trials in which training speed is specifically dosed. It is also necessary to explore the relationships between various training

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strategies and movement biomechanics to determine if improvements in RTD and rapid muscle activation result in functional gains.

## Conclusion

Typical rehabilitation strategies in the early period following knee surgery emphasize progressive ramp contractions and slower movements. Considering the significant deficits in the ability to rapidly fire the quadriceps muscle and develop force following surgery, coupled with the prominence of rapid submaximal muscle contraction and relaxation in the performance of most daily and sports activities, earlier performance of rapid muscle contractions following knee surgery may improve outcomes and assist in more rapid and complete normalization of function.

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Figure 4.1: Subject positioning for isometric testing of quadriceps muscle strength and RTD and for training with high intensity voluntary isometric knee extension contractions.

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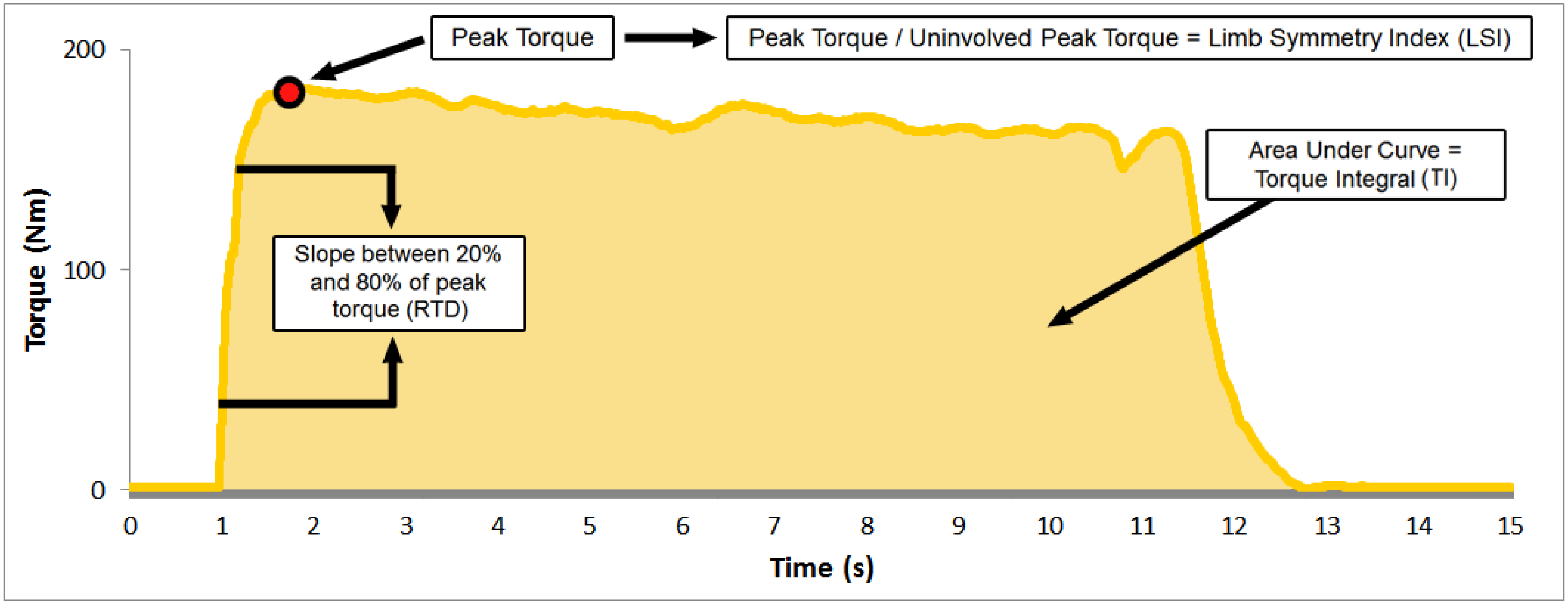

Figure 4.2: Variables calculated from voluntary isometric knee extension training repetitions. The sample repetition above indicates the rate of torque development (RTD20-80), strength (MVIC), and training intensity (TI and LSI).

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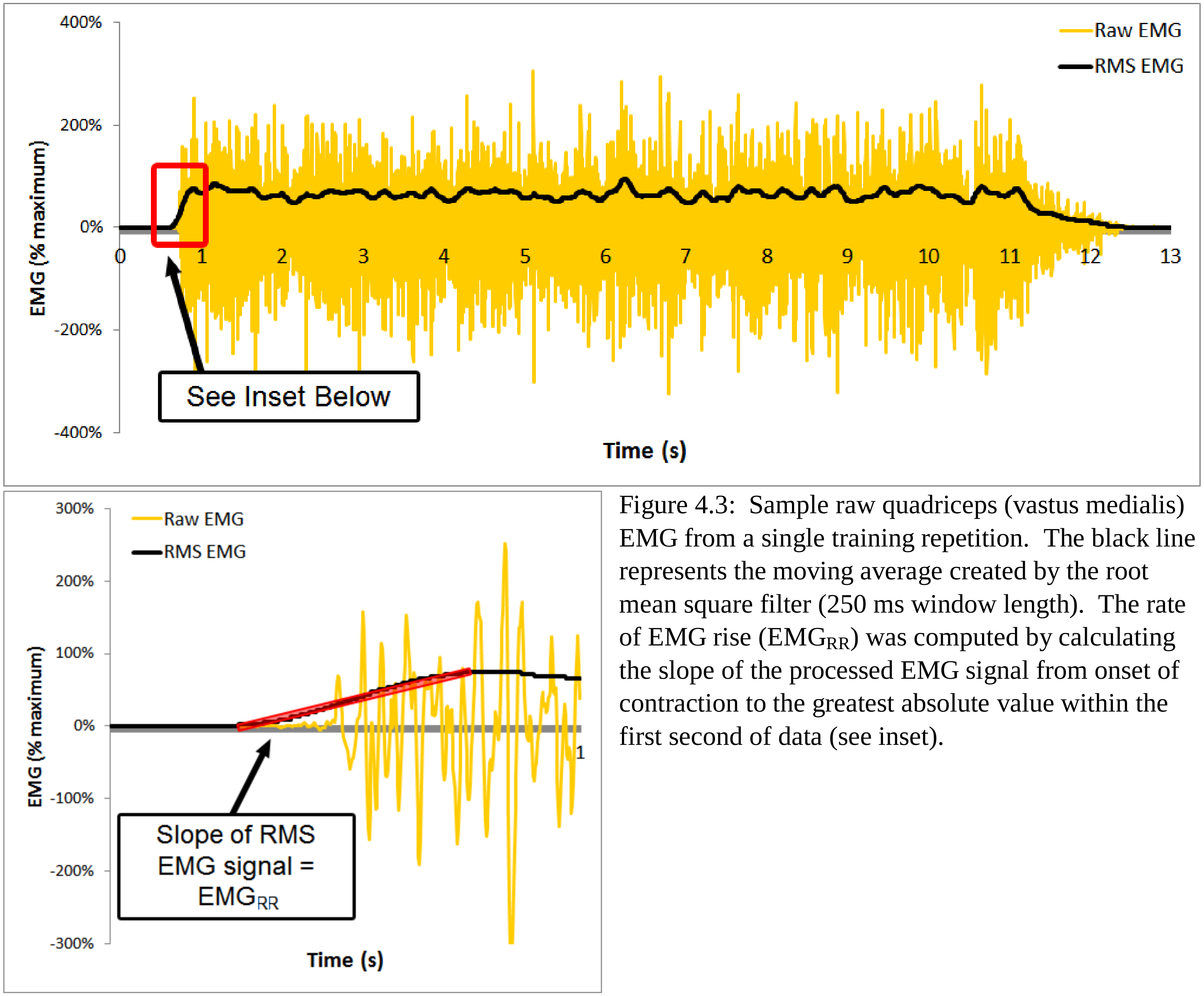

Figure 4.3: Sample raw quadriceps (vastus medialis) EMG from a single training repetition. The black line represents the moving average created by the root mean square filter (250 ms window length). The rate of EMG rise ($EMG_{RR}$) was computed by calculating the slope of the processed EMG signal from onset of contraction to the greatest absolute value within the first second of data (see inset).

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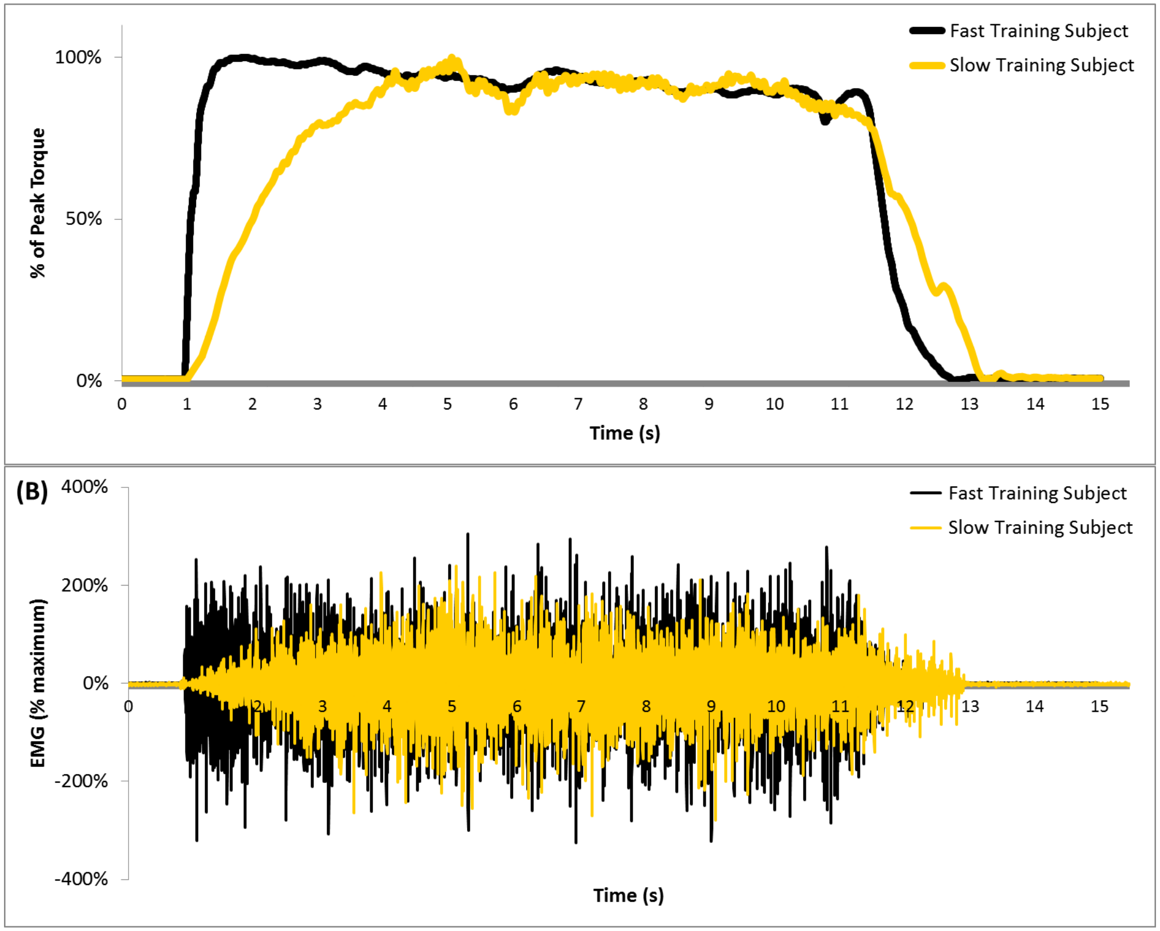

Figure 4.4: Sample torque (A) and raw vastus medialis EMG (B) recordings from the maximal voluntary isometric knee extension training repetitions of representative subjects of the $RTD_{FAST}$ and $RTD_{SLOW}$ groups. Torque (A) is normalized to percentage of peak torque and EMG (B) is normalized to the root mean square EMG amplitude at peak torque reached during that training session. Torque and EMG recordings are time synchronized.

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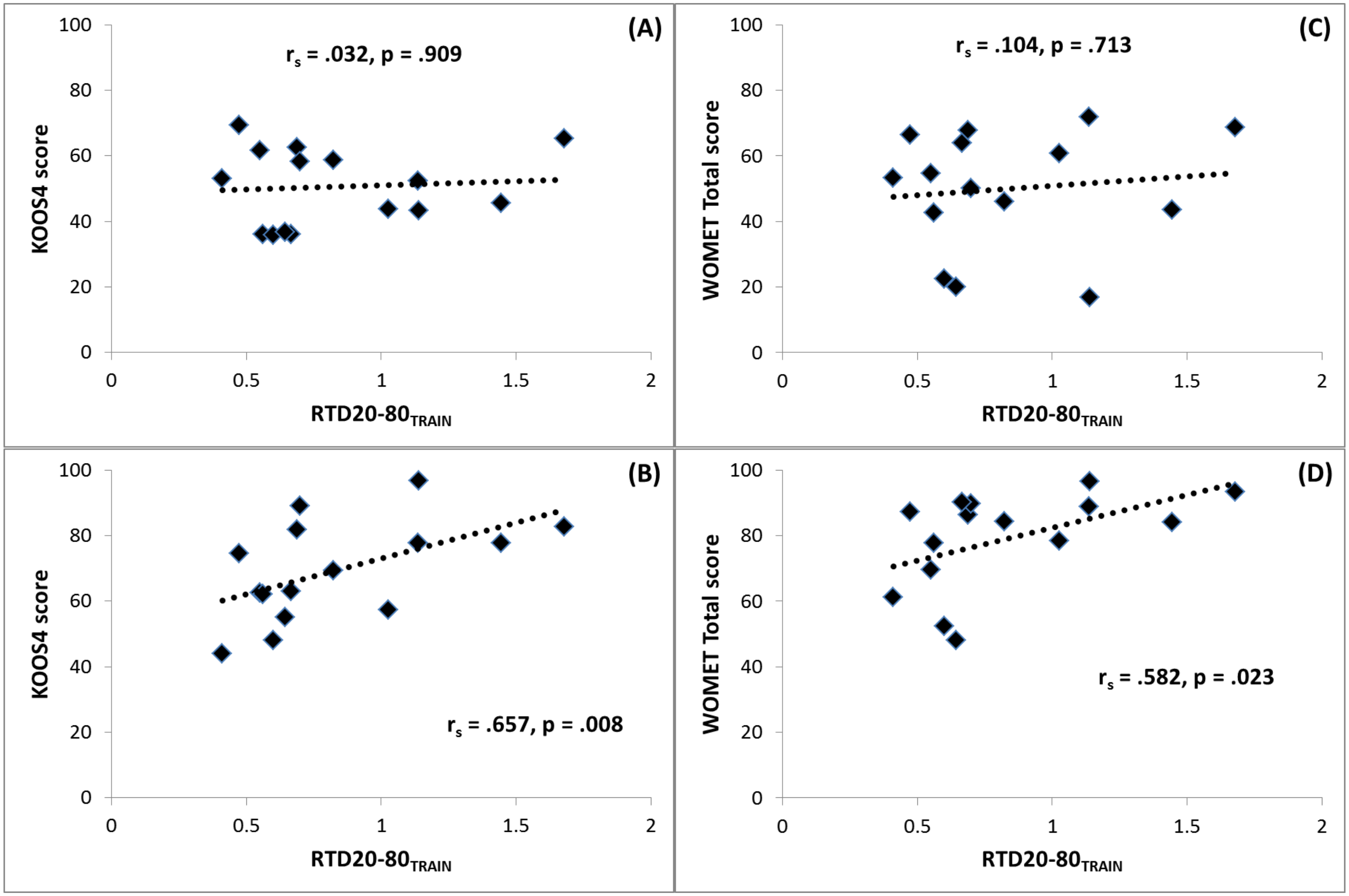

Figure 4.5: Correlations between $\text{RTD}_{\text{TRAIN}}$ and patient-based outcomes scores; A) KOOS4 scores pre-surgery; B) KOOS4 scores 5 weeks post-surgery; C) WOMET Total scores pre-surgery; D) WOMET Total scores 5 weeks post-surgery. Spearman's correlation coefficients ($r_s$) and p values are indicated on each scatterplot.

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Table 4.1: Treatment groups and exercise dosage throughout the ten training sessions which each subject completed

| Group | Quadriceps Exercise | Repetitions (volume) | Rest between Repetitions | Total Quadriceps Exercise Time |
|---|---|---|---|---|
| High Intensity Voluntary | 10 sec MVICs @ 90° | Visits 1-3: **10**<br>Visits 4-10: **20** | **30 seconds** | Visits 1-3: **6.5 min**<br>Visits 4-10: **13 min** |
| High Intensity Voluntary + NMES | 10 sec MVICs @ 90° + NMES | | | |

**Abbreviations:** MVIC, maximum voluntary isometric contraction; NMES, neuromuscular electrical stimulation

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Table 4.2: Subject characteristics, treatment groups, and training RTD

| Subject | Age | Sex | BMI | Treatment Group | DOS to 5wk post-test (days) | $\text{RTD}_{\text{TRAIN}}$ (95% CI) | $\text{RTD}_{\text{TRAIN}}$ / $\text{RTD}_{\text{TEST}}$ | KOOS4 Pre Sx | KOOS4 5wk Post-Surgery |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 52 | F | 23.5 | HI | 40 | 1.68 (1.58 - 1.78) | 45.2% | 65.2 | 82.6 |
| 2 | 42 | M | 27.3 | HI | 34 | 1.45 (1.40 - 1.49) | 38.3% | 45.6 | 77.8 |
| 3 | 42 | F | 32.3 | HI | 35 | 1.14 (1.07 - 1.20) | 41.3% | 52.4 | 77.6 |
| 4 | 20 | F | 27.7 | HI + NMES | 29 | 1.14 (1.06 - 1.22) | 44.1% | 43.3 | 96.9 |
| 5 | 54 | M | 25.9 | HI + NMES | 39 | 1.03 (0.97 - 1.09) | 24.1% | 43.7 | 57.3 |
| 6 | 31 | M | 28.9 | HI | 37 | 0.82 (0.81 - 0.84) | 23.9% | 58.7 | 69.3 |
| 7 | 20 | M | 23.3 | HI + NMES | 39 | 0.70 (0.66 - 0.73) | 17.8% | 58.3 | 89.0 |
| 8 | 36 | M | 25.1 | HI + NMES | 54 | 0.69 (0.65 - 0.73) | 16.6% | 62.6 | 81.9 |
| 9 | 56 | F | 24.2 | HI | 31 | 0.67 (0.63 - 0.70) | 28.7% | 36.1 | 63.0 |
| 10 | 38 | F | 24.5 | HI | 29 | 0.65 (0.61 - 0.68) | 21.8% | 36.8 | 55.1 |
| 11 | 59 | F | 32.5 | HI + NMES | 34 | 0.60 (0.56 - 0.64) | 21.4% | 35.9 | 48.1 |
| 12 | 24 | M | 28.5 | HI | 34 | 0.56 (0.53 - 0.60) | 18.3% | 36.1 | 62.1 |
| 13 | 46 | F | 21.8 | HI + NMES | 32 | 0.55 (0.53 - 0.57) | 17.0% | 61.6 | 62.6 |
| 14 | 18 | M | 24.5 | HI + NMES | 31 | 0.47 (0.42 - 0.52) | 14.3% | 69.3 | 74.7 |
| 15 | 61 | M | 27.1 | HI | 31 | 0.41 (0.39 - 0.43) | 18.6% | 53.0 | 44.1 |

**Abbreviations:** BMI, body mass index; DOS, date of surgery; $\text{RTD}_{\text{TRAIN}}$, rate of torque development during training repetitions (normalized to peak torque); CI, confidence interval; $\text{RTD}_{\text{TEST}}$, rate of torque development from maximal rapid voluntary isometric knee extension contractions performed during testing sessions.

$\text{RTD}_{\text{TRAIN}}$ / $\text{RTD}_{\text{TEST}}$ represents the percentage of maximal possible voluntary RTD that subjects trained with.

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Table 4.3: Correlations (Spearman's rs) between training RTD, training intensity, and changes maximal RTD, strength, and quadriceps volume from pre-surgery to 5 weeks post-surgery

|  | $RTD_{TEST}$ | MVIC/BW | QV |
|---|---|---|---|
| $RTD_{TRAIN}$ | .557* | .129 | .071 |
| $TI_{TRAIN}$ | -.057 | .121 | -.057 |
| $LSI_{TRAIN}$ | -.050 | .339 | -.125 |

**Abbreviations:** $RTD_{TRAIN}$, rate of torque development during training repetitions (normalized to peak torque); $TI_{TRAIN}$, Torque Integrals from training repetitions (normalized to MVIC); $LSI_{TRAIN}$, Limb Symmetry Index from training repetitions ((MVIC Involved/MVIC Uninvolved) * 100); $RTD_{TEST}$, rate of torque development from maximal rapid voluntary isometric knee extension contractions performed during testing sessions; MVIC/BW, maximum voluntary isometric contraction normalized to body weight; QV, quadriceps muscle volume
*Correlation is significant at the 0.05 level (2-tailed)

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Table 4.4: Comparison of subject characteristics, training RTD, maximal RTD, strength, quadriceps muscle volume, patient-based outcomes, and pain/VAS between $\text{RTD}_{\text{FAST}}$ and $\text{RTD}_{\text{SLOW}}$ groups

| **Group** | **AGE** | **BMI** | **UCLA (Pre)** | **$\text{RTD}_{\text{TRAIN}}$**** | **$\text{RTD}_{\text{TEST}}$** | | **MVIC/BW** | | **QV** | | **KOOS4** | | **WOMET Total** | | **VAS** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Pre | 5 wk* | Pre | 5 wk | Pre | 5 wk | Pre | 5 wk* | Pre | 5 wk* | Pre | 5 wk |
| $\text{RTD}_{\text{FAST}}$ | 42 ± 13.5 | 27.3 ± 3.2 | 7.6 ± 2.5 | **1.29 ± 0.3** | 3.12 ± 0.9 | **3.35 ± 0.6** | 2.38 ± 0.4 | 2.99 ± 0.6 | 19.6 ± 1.7 | 21.2 ± 2.1 | 50.1 ± 9.2 | **78.5 ± 14.2** | 52.3 ± 22.6 | **88.2 ± 7.2** | 1.33 ± 0.7 | 0.22 ± 0.3 |
| $\text{RTD}_{\text{SLOW}}$ | 41.6 ± 19.8 | 26.9 ± 4.0 | 6.8 ± 2.7 | **0.51 ± 0.1** | 4.40 ± 2.0 | **2.59 ± 0.3** | 2.79 ± 0.9 | 3.48 ± 1.4 | 21.2 ± 5.0 | 22.3 ± 5.3 | 51.2 ± 15.0 | **58.3 ± 12.3** | 47.9 ± 16.5 | **69.6 ± 13.6** | 1.24 ± 1.4 | 0.78 ± 0.8 |

**Abbreviations:** $\text{RTD}_{\text{FAST}}$, the group of five subjects who recorded the greatest $\text{RTD}_{\text{TRAIN}}$; $\text{RTD}_{\text{SLOW}}$, the group of five subjects who recorded the lowest $\text{RTD}_{\text{TRAIN}}$; BMI; body mass index; UCLA, UCLA Activity Score (pre-surgery); $\text{RTD}_{\text{TRAIN}}$, rate of torque development during training repetitions (normalized to peak torque); $\text{RTD}_{\text{TEST}}$, rate of torque development from maximal rapid voluntary isometric knee extension contractions performed during testing sessions; MVIC/BW, maximum voluntary isometric contraction normalized to body weight; QV, quadriceps muscle volume; KOOS4, Knee Injury and Osteoarthritis Outcome Composite Score; WOMET Total, Western Ontario Meniscal Evaluation Tool Total score; VAS, Visual Analog Pain Rating Scale
*Difference between groups is significant at the 0.05 level (2-tailed)
**Difference between groups is significant at the 0.01 level (2-tailed)

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Table 4.5: Correlations (Spearman's rs) between training rate of muscle activation, training RTD, maximal RTD, strength, quadriceps volume and patient-based outcomes scores from pre-surgery to 5 weeks post-surgery

| | $RTD_{TRAIN}$ / $RTD_{TEST}$ | MVIC/BW | QV | KOOS4 | WOMET Total |
|---|---|---|---|---|---|
| $EMG_{RR}$ | .600* | .118 | -.025 | .507 | .475 |

**Abbreviations:** $EMG_{RR}$**,** slope of the processed quadriceps electromyography signal from onset of contraction to the greatest absolute value within the first second of data during training repetitions; $RTD_{TRAIN}$, rate of torque development during training repetitions (normalized to peak torque); $RTD_{TEST}$, rate of torque development from maximal rapid voluntary isometric knee extension contractions performed during testing sessions; MVIC/BW, maximum voluntary isometric contraction normalized to body weight; QV, quadriceps muscle volume; KOOS4, Knee Injury and Osteoarthritis Outcome Composite Score; WOMET Total, Western Ontario Meniscal Evaluation Tool Total score.

$RTD_{TRAIN}$ / $RTD_{TEST}$ represents the percentage of maximal possible voluntary RTD that subjects trained with.

*Correlation is significant at the 0.05 level (2-tailed)

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# CHAPTER 5

## LOWER EXTREMITY POWER AND KNEE EXTENSOR RAPID FORCE DEVELOPMENT AFTER ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

### Introduction

Anterior cruciate ligament (ACL) injury and subsequent surgery characteristically leads to significant lower extremity neuromuscular dysfunction, particularly quadriceps muscle atrophy, weakness, activation failure, and diminished control of movement.(Eitzen et al., 2010, Ingersoll et al., 2008, Palmieri-Smith et al., 2008) Current evidence indicates that individuals who have sustained ACL injury and undergo surgery can and do return to sport, but many do so with abnormal muscle function or movement biomechanics (Hall et al., 2012, Noehren et al., 2013, Pollard et al., 2015, Tengman et al., 2015) and may be at increased risk of recurrent injury (Paterno et al., 2010) or long-term intra-articular degradation.(Hall et al., 2012, Lohmander et al., 2007) A recent investigation by Thomee et al. quantified lower extremity performance in patients who underwent ACL reconstruction with a battery of hop and muscle power tests before surgery and at 6, 12, and 24 months post-surgery.(Thomee et al., 2012) At 6 months post-surgery, not a single patient successfully completed the six lower extremity tests with a limb symmetry index of ≥ 90% (typically considered an acceptable level of muscle function due to the variability in these measurements). At 2 years post-surgery, only 23% of patients successfully completed the tests with a limb symmetry index of ≥ 90%. These types of thorough investigations of neuromuscular function indicate that we can improve the treatment, evaluation, and ultimately, outcomes of people who suffer ACL injury and reconstruction.

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Rehabilitation following ACL injury and surgery typically focuses on restoring lower extremity strength (quantified by the magnitude of resistance or load during an exercise). Objective measurements of leg function throughout this period are largely focused on peak strength. But, typical activities of daily living, such as ascending stairs, rising from a chair, and most sports activities require rapid force development, not maximal force development. It's rare that people, including athletes, actually produce maximal force during common tasks. Research in geriatrics and other populations suggests that functional ability, safety in movement, and patient-based outcomes are more closely related to rate of force development and power than they are to peak strength.

Angelozzi et al. recently investigated peak strength (quantified by maximal voluntary isometric contraction – MVIC) and rate of force development (RFD) during an isometric leg press task in 45 professional soccer players who sustained ACL rupture and underwent arthroscopic reconstruction. At 6 months post-surgery, MVIC of the involved limb was 97% of the pre-injury value while RFD was between 63% and 80% of the pre-injury value.(Angelozzi et al., 2012) People undergoing unilateral total knee arthroplasty present with diminished ability to rapidly produce knee extensor force in their involved limbs both prior to and after surgery. In these patients, side to side deficits in rate of torque development (RTD) were greater than deficits in maximum strength (MVIC).(Gapeyeva et al., 2007) In addition, subjective knee function was significantly correlated with quadriceps RFD asymmetry while MVIC asymmetry was not associated with subjective knee function.(Maffiuletti et al., 2010)

### Background/Rationale for Specific Aim 1

Investigations of human physiology and responses to training in healthy individuals have increased understanding of the neuromuscular factors which contribute to rapid muscle

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activation and force production. The ability of the neuromuscular system to rapidly increase contractile force is dictated by a variety of neural and structural factors. The absolute values of power and RFD are strongly moderated by the maximal force generating capabilities of the muscle.(Aagaard et al., 2002a, Andersen et al., 2010) Athletes who regularly perform explosive movements present with greater normalized measures of rapid force generation than endurance athletes or non-athletes,(Tillin et al., 2010) despite equivalent intrinsic contractile speed properties of the muscle. Increased agonist neural drive, potentially due to increased motor unit firing frequency, double discharges, or improved motor unit synchronization at the onset of contraction, results in improved capacity to rapidly develop force.(Aagaard et al., 2002a, Barry et al., 2005, Hakkinen et al., 1985, Van Cutsem et al., 1998) These changes are typically reflected by improved "early phase" RFD measurements (from onset of contraction to ~ 75 ms).(Andersen et al., 2010, Tillin et al., 2012) Following a training intervention, improvements in rapid force production are associated with elevated V-wave and H-reflex responses (Holtermann et al., 2007a), which indicate possible increases in motoneuron excitability and/or decreases in presynaptic inhibition.(Aagaard et al., 2002c) In a recent study of spinal and supraspinal factors associated with plantarflexor RTD, Johnson et al. concluded that supraspinal neural drive was the dominant predictor of RTD at all intervals.(Johnson et al., 2014)

Electrical stimulation with high pulse frequencies and pulse trains produces maximal muscle RFD and can be used to evaluate intrinsic muscle contractile speed properties.(de Haan, 1998, de Ruiter et al., 1999, Deutekom et al., 2000) The ratio of peak voluntary RFD/peak evoked RFD of the quadriceps is typically in the range of 30 to 50% (Buckthorpe et al., 2012, Cobian et al., 2015b, de Ruiter et al., 2007) and represents an individual's ability to utilize the

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maximal contractile speed properties of the muscle.(de Ruiter et al., 2007) This provides a measurement of the agonist neural drive during a rapid voluntary effort.(Tillin et al., 2012)

RFD is not a singular measure, but can be represented as a variety of interpretations of the force-time curve. Each of these measurements may provide different information concerning the neuromuscular determinants of RFD. Initial phase RFD (e.g., RFD from 0 to 50 ms) is strongly related to rapid neural activation of the quadriceps at the initiation of contraction (de Ruiter et al., 2004a, de Ruiter et al., 2007, Tillin and Folland, 2014, Tillin et al., 2010, Tillin et al., 2012), whereas later phase RFD (> 150 ms after contraction onset) is more strongly associated with maximal force capacity.(Andersen and Aagaard, 2006) Two individuals with similar intrinsic muscle speed properties could produce significantly different early phase RFD values based on the ability to rapidly drive the muscle.(Tillin et al., 2010)

Burst-superimposition techniques provide a method of measuring an individual’s ability to completely activate the quadriceps muscle during a maximal voluntary effort,(Shield and Zhou, 2004) and are frequently utilized in studies of quadriceps neuromuscular physiology. An electrical stimulus is provided to the quadriceps muscle during a MVIC, and the torque increment induced by the stimulation is used to calculate the percentage of Voluntary Activation (VA).(Herbert and Gandevia, 1999) The electrical stimulus is triggered when a subject reaches a near-maximal level of force production during a slow ramp contraction.(Krishnan et al., 2009) Thus, this method assesses the completeness of motor unit recruitment. However, it is the maximal motor unit discharge rate and/or rapid activation that are evidenced to be the primary neural determinants of maximal RFD.(Duchateau and Baudry, 2014) Despite normal levels of quadriceps VA, RFD may be limited by the inability to rapidly drive the muscle.

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At present it is known that the deficits in quadriceps RFD and power are greater than strength following knee injury and/or surgery (Angelozzi et al., 2012, Knezevic et al., 2014, Thomee et al., 2012), but the neuromuscular mechanisms contributing to these deficits have not been explored. Decreases in quadriceps activation and/or motor unit firing frequency occur with ACL injury and reconstruction.(Drechsler et al., 2006, Williams et al., 2005a) Quadriceps dyskinesia, or altered control of the voluntary activation and relaxation of the muscle, has been demonstrated to occur in ACL deficient subjects in both static and dynamic tasks.(Williams et al., 2004) Increased quadriceps electromechanical delay has also been reported in individuals post-ACL reconstruction (Kaneko et al., 2002), which may indicate abnormalities in excitation-contraction coupling. In individuals between 2 and 15 years post-ACL reconstruction, voluntary activation and normalized contractile speed properties of the quadriceps were similar between the involved limb and the healthy limb.(Krishnan and Williams, 2011)

The neuromuscular determinants of RFD, when evaluated in the context of the neuromuscular consequences of knee injury and surgery, provide strong evidence that deficits in quadriceps rapid force production following ACL reconstruction will be primarily due to the inability to rapidly voluntarily activate the muscle and not caused by side to side asymmetries of the intrinsic contractile properties of the quadriceps.

### Background/Rationale for Specific Aim 2

Abnormal neuromuscular function may contribute to aberrant knee biomechanics in gait and functional activities. Patients three to six months following ACL reconstruction with noted quadriceps weakness demonstrated reduced knee flexion angles and knee extensor moments during early stance phase.(Lewek et al., 2002) Recent evidence indicates that abnormal lower extremity biomechanics are observed during walking for at least two years after ACL

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reconstruction.(Roewer et al., 2011) Despite recovery of quadriceps strength deficits, subjects demonstrated decreased peak knee flexion, peak knee extensor moments, and peak knee power absorption during weight acceptance on the involved limb. Houck and Yack demonstrated similar deficits in an ACL deficient population who performed step down and cut activities.(Houck and Yack, 2003)

Normative gait data indicates that average step rate is roughly 110 steps per minute.(Drillis, 1961, Finley and Cody, 1970) Thus, the weight acceptance phase of gait (the first 10% of the gait cycle) lasts approximately 107 ms. Quadriceps activation increases significantly shortly after heel contact (Neuman, 2010), which indicates that the ability to rapidly develop quadriceps force may be of significant functional relevance in being able to attain normal gait biomechanics. For more intense locomotion activities, such as running, the functional relevance of rapid quadriceps activation is magnified as the time available to develop contractile force decreases. In older adults, slowed neuromuscular activation rate of the quadriceps has been shown to be associated with mobility limitations.(Clark et al., 2010, Clark et al., 2011) Thus, it is expected that deficits in the ability to rapidly produce quadriceps force will be associated with decreased knee flexion range of motion, peak knee extensor moments, and peak knee power absorption of the involved limb during stance phase in both gait tasks.

Single leg hop testing is a common clinical tool to assess leg function and readiness to return to sport following ACL reconstruction.(Barber et al., 1990) From a clinical perspective, hop testing is used as an efficient and cost-effective way of evaluating leg function.(Jarvela et al., 2002) More complex neuromuscular assessments, such as the procedures utilized in this investigation, are typically not clinically feasible. Single leg hop performance can predict self-reported knee function in people post-ACL reconstruction.(Logerstedt et al., 2012) Hop

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performance deficits following ACL surgery are related to abnormal function of the quadriceps (Schmitt et al., 2012), and people generate less knee power or demonstrate a reduced knee extensor moment during vertical hops.(Castanharo et al., 2011, Ernst et al., 2000)

However, the relationships between hop performance and quadriceps RFD and/or power following ACL reconstruction are unknown. In healthy subjects, quadriceps RFD, but not peak strength, was shown to be strongly related to vertical jump performance.(de Ruiter et al., 2006) It would be expected that limitations in the ability to rapidly develop force and/or produce power would manifest as deficits in single leg hop performance, but this has not been explored. If single leg hop performance were able to serve a surrogate clinical measure for RFD and/or power, that would provide further evidence for the clinical utility of these tasks.

### Background/Rationale for Specific Aim 3

The generation of maximal strength during an isometric effort may take 500 – 1500 ms (Jenkins et al., 2013, Thorstensson et al., 1976). However, the speed of most human movement precludes peak skeletal muscle force development. Many activities in daily life (walking, getting up from a chair, ascending or descending stairs) and sports (running, jumping) are accomplished by alternating patterns of rapid muscle activation and relaxation.(Cappellini et al., 2006, Coats-Thomas et al., 2013, Rand and Ohtsuki, 2000, Sung and Lee, 2009) Thus, the ability to rapidly develop force may be more meaningful to the performance of functional activities than the ability to generate peak force. Limitations in the ability to rapidly produce force could result in task failure (e.g. inability to prevent a fall)(Pijnappels et al., 2005) or suboptimal performance (e.g. slower acceleration).(Spiteri et al., 2015) In elderly individuals, measurements of muscle power and speed of activation have been shown to be more closely related to function than measurements of peak strength.(Accettura et al., 2015, Bento et al., 2010, Puthoff et al., 2008,

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Winters and Rudolph, 2013) Recent investigations have shown that side to side asymmetries in quadriceps rate of force development following total knee arthroplasty are larger than the deficits in maximal strength, and that subjective knee function is related to rate of force development, but not maximal strength.(Maffiuletti et al., 2010) In addition, knee extensor RFD, but not peak strength, has been shown to be related to self-reported knee function early after arthroscopic partial meniscectomy (Cobian et al., 2015b) and ACL reconstruction.(Hsieh et al., 2014) Based on the patterns of muscle activation and force production that people utilize to accomplish typical movements and tasks, measurements of RFD and power are expected to be more specific to function than peak strength, and would be more closely related to any deficits in function. Therefore, it is expected that patient-based outcomes scores after ACL reconstruction will be more strongly correlated with MRFD and peak power than MVIC or 1RM, and that subjects with greater deficits in the ability to rapidly produce force will record lower outcomes scores.

### Return to Sport after ACL Injury

Although typically evaluated on a case-by-case basis, athletes are frequently allowed to return to unrestricted activity 6 months after ACL reconstruction.(Kvist, 2004) Graft re-vascularization is largely complete by this time, although remodeling may continue to occur for up to a year after surgery.(Falconiero et al., 1998, Scranton et al., 1998) Patients may complete tests of lower extremity strength and function to monitor their progress during the rehabilitation period or pass acceptable threshold criteria in order to move on to the next phase of rehabilitation or return to sport.(Myer et al., 2006) Typically, these criteria involve tests of quadriceps strength (often with the use of isokinetics) and tasks thought to be representative of functional movements in sports, such as single leg hops for height or distance, balance and agility movements (Xergia et al., 2013), and evaluation of movement biomechanics during takeoff and landing.(Myer et al.,

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2008) The ability to rapidly produce force or maximize muscle power is rarely objectively measured as part of the testing process, despite the potentially significant functional consequences of limitations in these abilities.

In order to optimize treatment, we must fully understand the neuromuscular deficits related to ACL injury and surgery. More extensively evaluating the response of the neuromuscular system to trauma is the first step in identifying how we can have the greatest impact on overall function and long-term joint health.

The objective of this investigation was to characterize the deficits in rapid lower extremity force development after ACL reconstruction, and determine if and how the ability to rapidly develop force and generate LE power is related to movement biomechanics, common clinical tests of leg function, and knee-related quality of life. The central hypothesis of this proposal was that measures of rapid quadriceps force development are more sensitive than measures of peak strength after ACL injury, are limited by central mechanisms, and are more strongly associated with knee function and lower extremity biomechanics.

**Specific Aim 1**: Test the hypothesis that the deficits in knee extensor rate of force development (RFD) following ACL reconstruction are primarily the result of insufficiencies in the rate of voluntary neural activation at the initiation of contraction rather than peripheral contractile mechanisms or the ability to fully recruit the quadriceps at the time of peak force production.

*Hypothesis 1*: Subjects will demonstrate significant side to side asymmetries in the ratio of voluntary/evoked quadriceps RFD, quadriceps EMG RMS value from onset of contraction to 50 ms, and quadriceps RFD from onset of contraction to 50 ms. Contractile speed properties (assessed with pulse trains of electrical stimulation) will not be significantly different by limb.

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There will be no side to side asymmetry in quadriceps Voluntary Activation failure (assessed by modified triplet-superimposition method during a maximal voluntary contraction and at rest).

**Specific Aim 2**: Test the hypothesis that lower extremity biomechanics will be more strongly related to quadriceps RFD and lower extremity power than to peak leg strength after ACL reconstruction.

*Hypothesis 2*: Peak knee extensor moments and peak knee power absorption during the stance phase of both walking tasks will be more strongly correlated with RFD and LE power than MVIC or leg press 1RM. Single leg hop height and distance will be more strongly correlated with RFD/power than MVIC/1RM. Subjects with greater deficits in the ability to rapidly produce quadriceps force will demonstrate decreased knee flexion range of motion, peak knee extensor moments, and peak knee power absorption of the involved limb during stance phase in both gait tasks.

**Specific Aim 3**: Determine the associations between the ability to rapidly develop quadriceps force and lower extremity power after ACL injury and self-reported knee function.

*Hypothesis 3*: Self-reported knee function after ACL injury and reconstruction will be more strongly correlated with RFD and power than MVIC/1RM. Subjects with greater side to side asymmetries in the ability to rapidly produce force will record lower IKDC, KOOS, ACL-RSI, and TSK-11 scores.

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## Methods

### Subjects

18 subjects (9 males, 9 females, mean age 26.9 ± 6.8, mean BMI 26.9 ± 4.4 who recently underwent ACL reconstruction at the University of Iowa volunteered to participate in this study. All subjects were right leg dominant as determined by which leg they would primarily choose to kick a ball with. Testing sessions were completed between 4 and 12 months post-surgery (mean: 39.6 ± 10.3 weeks). Exclusion criteria included concurrent collateral ligament or articular cartilage procedure, lower extremity fracture or articular cartilage injury, history of quadriceps or hamstring muscle tear, and neural pathology or other medical conditions that could have resulted in safety concerns and adversely affected the health of the patient or the quality of the data. All subjects provided written informed consent in accordance with the guidelines of the University of Iowa Human Subjects Institutional Review Board.

### Testing Procedures

Tests of quadriceps muscle strength, activation, and speed properties, lower extremity power, and evaluation of movement biomechanics were completed at a clinically meaningful time period in subjects with recent ACL reconstruction. Data collections were split up into two sessions that were completed a minimum of 2 days apart. In the first session, subjects completed the assessment of movement biomechanics, and during the second session, completed tests of lower extremity neuromuscular performance. During the neuromuscular test session, subjects completed all tests and measures with their uninvolved leg first.

### Lower Extremity Power Testing

Subjects were seated on an instrumented leg press device (Keiser A420, Keiser Inc., Fresno, CA) specifically designed for evaluation of lower extremity power. Subjects were

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positioned with hip and knee angles of approximately 115 and 90 degrees, respectively. Feet were centered on the pedals in both the anterior/posterior and medial/lateral directions (Figure 1). To familiarize with the device, subjects performed warm up repetitions with low resistance and velocity. Subjects completed 1RM testing following NSCA guidelines.(Miller, 2012), and were instructed to attempt to extend the knee from the initial flexed position to 0 degrees of flexion, resting for 1 minute between efforts.

Once 1RM was reliably attained, subjects were instructed in performance of the leg press power task. Subjects were instructed to push out against the foot pedals as fast and as hard as possible. Trials were initiated from rest with an audio signal. Subjects completed a minimum of three practice trials and five recorded trials, resting for 30 seconds between each repetition. Power repetitions were completed with resistance set at 40% of the highest 1 RM value achieved with the ipsilateral leg. Feedback of peak power produced on the previous repetition was provided using the leg press device's real time data analysis capabilities. After 2 minutes of rest, the same procedure was completed with resistance set to 70% of 1RM. This is an efficient test design to characterize power production at two distinct points on the force/velocity curve.(Cuoco et al., 2004)

### Testing of Muscle Contractile Properties, Strength, Activation, and RFD

Test order was consistent within and between subjects: contractile properties, strength/activation, and RFD. To minimize impedance prior to placement of EMG preamplifiers, skin preparation was completed with Nuprep Skin Prep Gel (Weaver and Co., Aurora, CO). Surface EMG electrodes (model 544, Therapeutics Unlimited, Iowa City, IA) were applied over the muscle bellies of the vastus lateralis (VL), rectus femoris (RF), vastus medialis

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(VM), semitendinosus (ST), and biceps femoris (BF) using Ten20 Conductive Paste (Weaver and Co., Aurora, CO).

Subjects were seated on the chair of a FDA approved Testing & Rehabilitation System containing a servo motor (HUMAC NORM, Computer Sports Medicine, Inc., Stoughton, MA, USA) used to test muscle strength, control, and perform rehabilitation. The limb being tested was affixed to the device by way of a soccer shin guard attached to the testing limb, 5 cm proximal to the medial malleolus. A strain gauge transducer was tightly secured to the front of the shin guard and attached to the knee testing adapter, which could be adjusted to facilitate an appropriate fit to subjects of various heights. The knee testing adapter was fixated such that there was no compliance or slack in the system when subjects performed a voluntary knee extensor contraction and kicked into the shin guard. This methodology allowed proper evaluation of rapid isometric force production without a dampening or amplification effect of the force signal that can occur in a non-rigid setup.(de Ruiter et al., 2004a) The hip was fixed at approximately 90° of flexion and the knee was fixed at 60° of flexion during testing (Figures 2A and 2B).(Krishnan and Williams, 2014)

**Contractile Properties**

Self-adhesive muscle stimulation (2.75” x 5” Dura-stick electrodes, Chattanooga Medical Supply, Inc., Chattanooga, TN, USA) electrodes were applied to the subject’s anterior thigh.(Place et al., 2010) Subject-specific stimulus intensity was determined for use in testing contractile properties and quadriceps activation testing. This was accomplished by stimulating the quadriceps muscle with increasing stimulation current (beginning at 50 mA) until force production plateaued (subsequent increases decrease force) using an FDA approved constant current muscle and nerve stimulator (Digitimer Ltd., Model DS7AH, Hertfordshire, England)

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while the subject sat at rest. 110% of the intensity required to produce peak twitch torque was used for contractile properties and voluntary activation tests.(Behm et al., 1996) This approach ensured collection of quality data at the lowest possible stimulus intensity, thereby maximizing subject comfort. After one minute of rest, contractile properties of the quadriceps muscles were assessed with electrically evoked pulse trains (multiple pulses in series). To ensure maximal RFD was obtained, an eight pulse train, or octet (300 Hz, 100 µs pulse duration, 400 V), contraction was elicited. This protocol was based on previously published literature and pilot testing in our laboratory, with the goal of obtaining peak force and RFD from electrically evoked quadriceps contractions while minimizing subject discomfort. The octet stimulation protocol has been demonstrated to be effective in maximizing rapid force production.(Buller and Lewis, 1965, de Haan, 1998, de Ruiter et al., 2004a, Deutekom et al., 2000) However, this high intensity stimulation protocol can be painful, which some subjects cannot tolerate.(Tillin et al., 2012) Octet stimulation is highly reproducible and a reliable method for evaluating the rapid contractile capacity of the knee extensors.(Buckthorpe et al., 2012) Thus, a single octet trial was expected to accurately characterize evoked RFD capacity while minimizing subject discomfort.

### Quadriceps Strength, RFD, and Voluntary Activation

After completing the contractile properties test, subjects performed quadriceps strength, RFD, & activation testing. Subjects completed sub-maximal warmups (50%, 75%, 90% of maximum effort) and a minimum of two maximal isometric knee extension contractions to reliably determine peak voluntary knee extensor force. Trials continued until two repetitions in which peak force did not vary by greater than 5% were recorded. After peak force was reliably identified, subjects were instructed in the performance of rapid voluntary isometric contractions. Subjects were provided with explicit instructions regarding the goal of each effort, and given

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loud verbal encouragement, as both of these concepts are important in inducing a voluntary contraction that maximizes rapid force production.(Holtermann et al., 2007b, Sahaly et al., 2001) Following practice trials, a minimum of 5 RFD trials were performed, with 30 seconds of rest between each repetition. Trials were initiated from rest by an audio signal and subjects were encouraged to continue kicking for 3-4 seconds until force production plateaued, at which point they were instructed to relax. Efforts with a countermovement prior to the rise in force (de Ruiter et al., 2007) were discarded. Voluntary activation testing was performed utilizing a burst-superimposition method.(Snyder-Mackler et al., 1994) A threshold was set based on previously established MVIC, and triplet stimulation (100 Hz, 100 µs pulse duration, 400 V, supramaximal current intensity) was triggered when the torque threshold was reached.(Krishnan et al., 2009) A formula based on the interpolated twitch technique was used to determine voluntary activation.(Krishnan and Williams, 2010)

### Hamstrings Strength and RFD

Following completion of the quadriceps testing protocol, the shin guard and load cell attachment were repositioned on the posterior surface of the subject’s calf. Subjects again completed sub-maximal warmups (50%, 75%, 90% of maximum effort) of knee flexion contractions. Maximal isometric knee force production was obtained with a minimum of two trials in which peak force did not vary by greater than 5%. Subjects were then instructed to perform knee flexor RFD contractions with explicit directions to pull back as fast and as hard as possible into the shin guard until instructed to relax. A minimum of 5 RFD trials, initiated by an audio signal, were completed with 30 seconds of rest between each repetition.

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Following completion of the hamstring testing protocol, subjects were removed from the testing apparatus and rested for 5-10 minutes while equipment was prepared for collection of the contralateral (involved) leg.

**Movement Biomechanics: Walking and Stepping Down**

Subjects completed gait trials over level ground and well as stepping down from curb height. An Optotrak motion analysis system (Model 3020, Northern Digital Inc., Waterloo, Ontario, Canada) was used to record the three dimensional coordinates of infrared emitting diode (IREDs) clusters at 60 Hz. Triads of IREDs were secured on the pelvis and on the thighs, legs, and feet bilaterally with double-sided tape and fabrifoam (Fabrifoam Products, Exton, PA, USA) to create anatomical segments. An in ground force plate system (two force plates aligned in tandem) was utilized for both gait tasks (Model 9865B, Kistler Instruments, Inc., Amherst, NY), with force plate data recorded at 360 Hz. Anatomical landmarks were digitized with the subject standing in a neutral position.

Subjects walked along a 10 meter runway, with cadence matched to a metronome, at a rate of 113 steps/second, approximately the average step rate in healthy populations.(Drillis, 1961, Finley and Cody, 1970) After completing practice trials to adapt the appropriate cadence and consistent heel strike within the borders of the force plates, subjects completed five recorded trials. To produce the step down trials, a portable walkway 20 cm in height was positioned above the runway. A step was secured to the first force plate that matched the height of the walkway and subjects walked on the platform at the noted cadence, then stepped down onto the second force plate, and continued to walk forward, as if stepping off of a curb and onto the street (Figure 3). The runway was 4.6 m in length and the distance from the edge of the runway to the

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center of the step was 41 cm.  For the step down trials, subjects stepped off of the uninvolved leg first (landing on the involved leg).

### Vertical Hop (VH)

Subjects completed single leg vertical hops (VH) standing on the force plate.  Subjects were instructed to attempt to maximize hop height, and were allowed to use a countermovement, trunk flexion, and/or arm swing to accomplish this goal (Figure 4).  Practice trials were performed until subjects were comfortable performing the task with maximal effort.  As the purpose of the collection was to evaluate knee biomechanics during the takeoff portion of the hop, and maximize hop height, subjects were allowed to use the opposite leg to aid in stabilization after landing.  Subjects completed five recorded trials with rest periods of at least 30 seconds between test trials.  The uninvolved limb was tested first.  Motion capture data was recorded at 60 Hz and force plate data was recorded at 360 Hz.

### Single Leg Hop for Distance (HFD)

Subjects also performed single leg hops in the forward direction with a goal of maximizing the hop distance within the sagittal plane.  Practice trials were completed until subjects could confidently perform the task with maximal effort.  Subjects aligned their foot in the center of the force plate and were instructed to hop as far forward as possible.  Subjects were instructed to make initial ground contact with the foot of the hopping leg, but were allowed to make ground contact with the opposite foot after landing to assist in maintaining balance.  Five trials were completed with rest periods of at least 30 seconds between trials.  The uninvolved limb was tested first.  Motion capture data was recorded at 60 Hz and force plate data was recorded at 360 Hz.  For both VH and HFD, only motion capture data during the takeoff portion of the movement was collected.

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## Patient-based Outcomes Measures

Subjects completed the Knee Injury and Osteoarthritis Outcomes Score (KOOS), the International Knee Documentation Committee Subjective Knee Form (IKDC), the ACL Return to Sport Index (ACL-RSI), a Global Knee Rating Scale score (GKRS), and the abbreviated version of the Tampa Scale for Kinesiophobia (TSK-11). These are valid and reliable instruments for evaluating patient-reported knee function, readiness for return to sport, and kinesiophobia in this population, and are commonly used to assess clinical outcomes.(Irrgang et al., 2001, Roos et al., 1998, van Meer et al., 2013) The IKDC contains items that are both important to and frequently experienced by patients less than 12 months after ACL reconstruction. The KOOS Sports/Recreation and KOOS4 composite score was used in the final analysis. The KOOS sports/recreation subscale contains items that are highly important to patients who have undergone ACL reconstruction. These items are not fully represented in the IKDC and therefore are not redundant.(Hambly and Griva, 2010) The ACL-RSI was found to be a strong predictive parameter for assessing return to sport in patients 6 months s/p ACL reconstruction.(Muller et al., 2014) The TSK-11 may help identify patients who are unable to return to preinjury levels of sports participation following ACL reconstruction due to psychosocial factors.(Lentz et al., 2015) Pain during activity was assessed with a 100 mm Pain-Visual Analog Scale (VAS), which subjects completed following the walk and step down task, with instructions to rate their level of pain experienced in association with the task.

### Signal Sampling and Processing

*Force and EMG Signals*

Custom software in LabChart v 8.0.8 (ADInstruments, Inc., Colorado Springs, CO) was utilized to record and process force and EMG data. Force and EMG signals were sampled at 2000 Hz. Force signals were low pass filtered with a cutoff frequency of 50 Hz and EMG

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signals were band pass filtered with a range of 20-500 Hz. High sampling rates ensured proper resolution, an important aspect of evaluating RFD and changes in EMG in very short time windows.

*RFD from Voluntary and Electrically Elicited Contractions*

Voluntary and electrically evoked knee extensor RFD trials and voluntary knee flexor RFD trials were processed with custom algorithms created using Python programming language (Python Software Foundation, Beaverton, OR). Force and EMG onset were defined with the same protocols utilized in previous investigations (see Appendix). Onset of contraction must be accurately and reliably identified to properly quantify the early rate of rise in force and muscle activation.(Tillin et al., 2013) MRFD is defined as the single data point at which the greatest positive slope (N/s) of the force signal occurs. Force increment in consecutive windows from 0-50 ms, 50-100 ms, and 100-200 ms ($F_{0\text{-}50}$, $F_{50\text{-}100}$, and $F_{100\text{-}200}$, respectively) from the onset of contraction were computed. The percentage of peak voluntary force reached at 50 ms, 100 ms, and 200 ms from the onset of contraction ($F_{50}$, $F_{100}$, and $F_{200}$, respectively) were computed to provide force normalized measures of RFD. Force time integrals (FTI) were also calculated, as was the slope of the force signal from 20% of the peak force to 80% of the peak force ($RFD_{20\text{-}80}$). As discussed in previous chapters, each of these measurements can provide unique and valuable information about the neuromuscular determinants of RFD. The best three out of five efforts for each variable were averaged to produce a single value for each variable at each time point with each leg. This is the typical approach for evaluating voluntary RFD due to the greater variability in maximal voluntary rapid force production.(Tillin et al., 2011, Tillin et al., 2012) Limb symmetry indices (LSI) were calculated for all variables.

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### *Leg Press 1RM, Power, and Acceleration*

Leg press power and acceleration was sampled at 400 Hz (the maximum sampling rate of the Keiser leg press system). Leg press strength (LP 1RM) was determined from 1RM testing. Peak power and peak acceleration were calculated from each explosive effort performed at 40% and 70% of 1RM ($PP_{40}$, $PP_{70}$, $PA_{40}$, and $PA_{70}$). The best three out of five were averaged to produce a single value, which was normalized to body weight (kg). Peak acceleration values were also normalized to the resistance on each repetition. LSI values were calculated for each variable.

### *EMG Signals from Voluntary RFD Contractions*

EMG signals obtained from the quadriceps during voluntary knee extensor RFD trials were processed with custom Python scripts. Electromechanical delay (EMD) - the difference in time between onset of force and EMG signals - was calculated for each muscle. Total reaction time (TRT), the time between the start of the audio signal and the onset of force production, was also computed for each trial. Root mean square (RMS) amplitude of each EMG signal was computed from onset to various time points to align with force data (e.g. $VL_{0\text{-}50}$ for RMS value from VL EMG onset to 50 ms). All EMG calculations were normalized to peak RMS EMG amplitude (500 ms moving window) generated during ramp MVIC contractions (matched by leg). After normalization, RMS EMG values were averaged across the three quadriceps muscles to create a mean quadriceps value (e.g. $QUAD_{0\text{-}50}$ for combined quadriceps RMS value from onset to 50 ms). EMD, TRT, and RMS amplitudes were also calculated for ST and BF EMG signals collected during voluntary knee flexor RFD trials. A hamstrings combined RMS EMG value was also created (e.g. $HS_{0\text{-}50}$ for combined ST and BF RMS value from onset to 50 ms).

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### *Movement Biomechanics*

Kinematic gait data during walking and step down trials was low-pass filtered (6 Hz) with a zero phase lag, fourth-order Butterworth filter, with a 12 Hz filter used for hopping trials. Lower extremity knee joint moments and powers were calculated using individually scaled models (Visual 3D, C-Motion, Rockville, MD). Peak knee extensor moment and peak knee power absorption of the stance limb were averaged over the five recorded trials and were the primary variables of interest during gait and step down trials. Knee joint moments and powers were time normalized and ensemble averaged by limb. VH height was calculated with the flight time method.(Linthorne, 2001, Moir, 2008) Single leg HFD was measured during each trial with a tape measure. For both hopping tasks, the best three out of five efforts were used in the final analysis of hop height or distance.(Moir et al., 2008) Peak knee extensor moment and peak knee power generation during the takeoff portion of the vertical and forward hop were also computed.

## Data Analysis

All statistical analyses were performed with IBM SPSS version 23.0 (IBM Corporation, Armonk, NY). Data was compiled and descriptive statistics and effect sizes (Cohen’s d) were calculated for all variables. The primary outcome variables were normally distributed (as assessed by Shapiro-Wilk’s test), so parametric statistics were utilized for hypothesis tests and correlational analysis. Absolute differences between involved and uninvolved limbs were analyzed with student’s paired t-tests. Differences between side to side asymmetries in peak force and RFD variables were analyzed using one-way repeated measures ANOVA. Post hoc testing with a Bonferroni correction was utilized to determine significance of pairwise comparisons. Pearson’s product-moment correlation was performed to evaluate the associations

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between quadriceps strength, RFD, movement biomechanics, and patient-based outcome measures. A significance level of $\alpha = .05$ was used for all analyses.

## Results

### Subjects

Complete subject demographics are shown in Table 5.1. In regards to the initial ACL rupture, thirteen subjects sustained a noncontact injury, three subjects suffered a contact injury, and the injury mechanism was unclear in the remaining two subjects. Two subjects sustained a concurrent MCL injury, which in both cases was treated conservatively. Ten subjects underwent ACL reconstruction of the right (dominant) leg, while eight sustained injury and had subsequent repair of the left (nondominant) leg. Surgery was performed by one of five fellowship trained University of Iowa sports medicine surgeons. Ten subjects were found to have partial tears of the medial (2) or lateral (8) meniscus, which were debrided in seven cases and unaltered in two cases. One subject underwent a concomitant lateral meniscus repair of a 15 mm vertical tear. A bone-patellar tendon-bone (BPTB) autograft was used for ACL reconstruction in six subjects, while the other twelve underwent repair with semitendinosus-gracilis (STG) autograft.

All subjects followed the MOON ACL rehabilitation protocol after surgery.(Wright et al., 2015) In all but one case, the first documented outpatient physical therapy visit occurred within two weeks of surgery. No subjects in this study sustained any subsequent knee injury between ACL reconstruction and completion of the study procedures. Two subjects who received a BPTB graft did complain of residual pain at the donor site, though none of the subjects who participated in this study reported knee pain that inhibited their performance of any of the tasks or procedures.

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Common clinical measurements (Table 5.2) included knee joint circumference, leg circumference 10 cm proximal to the base of the patella, passive knee range of motion, and assessment of anterior laxity with a KT-2000™ arthometer. For all variables analyzed in this investigation, there were no significant differences in strength or RFD by graft type, sex, or dominance of the surgical leg.

### Strength and RFD

#### *Quadriceps*

Absolute values of mean knee extensor strength (MVIC) and MRFD of the involved limb were significantly lower than the uninvolved limb. Effect sizes were greater than 0.8 for differences in strength and ranged from 0.29 to 1.25 for absolute RFD variables. LSI values for MVIC and MRFD were nearly identical (81.1% and 81.2%, respectively). When normalized to MVIC, there were no significant differences in knee extensor RFD between limbs, for both early ($F_{50}$) and late phase ($F_{200}$) variables. When the force-time curve was analyzed in short, consecutive windows, $F_{100-200}$ was found to have both the lowest LSI value (63.8 ± 30.6%) and the greatest effect size (Cohen's d = 1.25) of any strength or RFD variable (Table 5.3).

#### *Hamstrings*

Peak knee flexion strength of the uninvolved leg averaged 4.6 ± 1.3 N/kg and was 4.4 ± 1.3 N/kg for the involved leg. This difference was not significant. Mean LSI values for knee flexor RFD variables ranged from 91.7% to 115.3%, and there were no significant differences between limbs (Table 5.4). Normalized early phase hamstring RFD ($F_{50}$ and $F_{100}$) was significantly lower than early phase quadriceps RFD (p values from < .001 to .004). Late phase ($F_{200}$) normalized RFD was similar between quadriceps (66.6 to 70.6%) and hamstrings (73.0 to 76.1%). Subjects with a STG had a mean normalized knee flexion MVIC of 4.2 N/kg compared

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to 4.7 N/kg in subjects who received a BPTB graft. However, there was significant variability within these groups (5/12 STG subjects had LSI values of < 85%, while 4/12 had LSI values of > 100%), and this difference was not significant.

### Quadriceps Contractile Properties and Voluntary Activation

Four subjects were unable to tolerate the quadriceps stimulation protocol; thus, only fourteen subjects are included in this portion of the analysis. Mean octet peak force and MRFD were lower in the involved limb, but these differences were not statistically significant (Table 5.5). Normalized voluntary RFD as a percentage of normalized Octet RFD was nearly equal bilaterally (51 ± 20% and 50.9 ± 16.4%, respectively). Voluntary peak force and octet peak force LSI values were strongly positively correlated ($r = .683$, $p = .01$). Mean quadriceps voluntary activation was similar between the involved (80.4 ± 12.0%) and uninvolved (79.5 ± 12.5%) limbs. VA LSI values were not correlated with KE MVIC LSI values.

### EMG and EMD during RFD trials

#### *Quadriceps*

TRT was similar between involved (362 ± 38 ms) and uninvolved (370 ± 32 ms) limbs. In addition, EMD for the VL, RF, and VM was similar between limbs and did not vary by muscle. There were no significant side-to-side differences in group mean values of quadriceps RMS EMG produced during the initial period of knee extensor RFD trials when RMS values were computed from EMG onset (Table 5.6). $VM_{100\text{-}200}$ was significantly lower in the involved limb (LSI: 82.5 ± 23.5%, $p = .006$). $QUAD_{100\text{-}200}$ was also 9.1% lower in the involved limb, but this difference did not reach statistical significance. $VM_{0\text{-}50}$ was significantly greater than $RF_{0\text{-}50}$

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for both the uninvolved (p = .048) and involved (p = .011) limbs. $QUAD_{0\text{-}200}$ was more strongly correlated with $F_{200}$ (r = .676, p = .002) than $QUAD_{0\text{-}50}$ was with $F_{50}$ (r = .519, p = .027).

*Hamstrings*

There were no side-to-side differences in TRT during knee flexor RFD trials (Uninvolved: 342 ± 40 ms; Involved: 339 ± 45 ms). EMD of the ST and BF was similar between limbs (Table 5.6) and did not vary by muscle. TRT during knee flexor voluntary RFD trials was significantly lower than TRT during knee extension trials (p = .003 and .020 for the uninvolved and involved limbs, respectively). Combined quadriceps EMD was significantly longer than combined hamstrings EMD for both the uninvolved (p = .017) and involved (p = .030) limbs.

### Leg Press Strength, Power, and Acceleration

LP 1RM averaged 8.33 ± 1.7 N/kg for the uninvolved limb and 7.36 ± 2.3 N/kg for the involved limb. This side-to-side asymmetry (LSI: 87.1 ± 15.1%) was significant (p = .004). All leg press PP and PA measurements (at both 40% and 70% of 1RM) were significantly different by side. Effect sizes ranged from 0.29 to 0.82 (Table 5.7). $PP_{40}$ and $PA_{40}$ LSI values (82.4 ± 14.7% and 78.9 ± 16.8%) were significantly lower than LP 1RM LSI values when assessed with a repeated measures ANOVA followed by post hoc tests with a Bonferroni correction (p = .014 and .003, respectively).

### Movement Biomechanics

Peak knee extensor moments of the involved limb were significantly lower than uninvolved limb moments during the stance phases of gait over level ground (p = .022), stepping down with both the leading (p < .001) and trailing limbs (p < .001), and during single leg VH (p < .001) and HFD (p = .004). Similar differences in group means were found for peak knee power absorption during weight acceptance and generation during takeoff (Table 5.8). Peak

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knee moment LSI value calculated during walking trials averaged 84.9 ± 30.1%. Comparatively, the peak knee moment LSI of the leading limb during the walk and step down task averaged 68.0 ± 28.4% and was 66.7 ± 34.4% and 75.7 ± 21.5% for the single leg vertical hop and single leg hop for distance, respectively. Mean VH height was 15.4 ± 4.2 cm with the uninvolved leg and 11.4 ± 5.2 cm with the involved leg. This difference (LSI of 69.5 ± 22.3%) was significant ($p < .001$). Subjects produced a mean forward HFD of 159.8 ± 30.8 cm with the uninvolved leg and 142.5 ± 40.8 cm with the involved leg. This difference (LSI of 88.1 ± 16.2%) was also significant ($p = .004$). There were also significant differences found between the LSI values of mean peak knee power and VH height ($p = .035$), and between the LSI values of mean peak knee extensor moment and HFD distance ($p = .005$), and the LSI values of mean peak knee power and HFD distance ($p = .005$). Knee extensor moments and powers during walking and stepping down were ensemble averaged and are depicted in Figure 5.4.

### Correlations between Movement Biomechanics and Muscle Performance

LSI values of closed chain LP 1RM, $PP_{40}$, and $PA_{40}$ were strongly positively correlated with single leg VH and HFD peak knee moments, peak knee powers, and hop performance (height and distance). $PP_{40}$ and $PA_{40}$, but not LP 1RM, were significantly positively correlated with peak knee power during walking (Table 5.9). LP 1RM, $PP_{40}$, and $PA_{40}$ LSI values were strongly positively correlated with peak knee moments and powers during the step down movement, with Pearson’s r values being slightly larger with power and acceleration asymmetries than strength asymmetries.

Knee extensor MRFD and $FTI_{0\text{-}200}$ LSI values were generally strongly positively correlated with hop performance (Table 5.10). Knee extensor MVIC was only significantly correlated with single leg VH height. In addition, knee extensor MRFD was significantly

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positively correlated with peak knee extensor moment and peak knee powers during walking, while knee extensor MVIC was not. Knee flexor strength and RFD variables were not significantly correlated with movement biomechanics.

### Correlations between Patient-based Outcomes Measures and Muscle Performance

Closed chain LP 1RM, $PP_{40}$, and $PA_{40}$ were generally strongly positively correlated with GKRS, ACL-RSI, IKDC, and KOOS scores (Table 5.11). There were no differences in the strength of the correlations between 1RM and PP or PA. Knee extensor MVIC LSI values were weakly positively correlated with outcomes scores. Conversely, knee extensor $FTI_{200}$ and $RFD_{20\text{-}80}$ LSI values were significantly positively correlated with IKDC, KOOS Sports & Recreation, and KOOS4 composite scores (Table 9). TSK11 scores were not associated with any muscle performance variables. In addition, knee flexor strength and RFD variables were not significantly correlated with any outcomes scores, though there were non-significant moderate positive correlations between knee flexor MVIC LSI and KOOS scores.

## Discussion

The purpose of this investigation was to evaluate rapid lower extremity power and force development in people from six months to one year post-ACL reconstruction and determine if these characterizations of neuromuscular performance are related to movement biomechanics, typical clinical measures of readiness to return to activity, and patient-based outcomes. This was a comprehensive investigation of lower extremity neuromuscular performance related to rapid force development that is the first of its kind in this subject population.

The hypotheses of this investigation were partially supported. There were significant side-to-side asymmetries (approximately 20%) in voluntary rapid knee extensor force production

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in this population of subjects having undergone ACL reconstruction. However, there were no significant differences in the rate of voluntary quadriceps activation between limbs during the initial portion of rapid isometric knee extension efforts.

Leg press power, acceleration, and knee extensor MRFD were significantly correlated with knee joint biomechanics during walking over level ground. Knee joint kinetics and maximal height and distance achieved during single leg hopping tasks were strongly positively correlated with leg press performance. Knee extensor RFD was more strongly correlated with performance of single leg hopping tasks than MVIC.

Knee extensor RFD was also (significantly) correlated with KOOS and IKDC scores, while knee extensor MVIC was not. Leg press 1RM, power, and acceleration were all strongly correlated with outcomes scores.

Voluntary activation failure during maximal voluntary contraction, assessed by triplet-superimposition method, was not significantly different between limbs. Conversely, the mean LSI value of peak force induced by octet stimulation at rest was 89%, and octet peak force was strongly positively correlated with voluntary knee extensor MVIC, indicating the discrepancy in RFD variables was primarily due to asymmetries in the maximal force generating capability between the quadriceps muscles of the involved and uninvolved limbs. The deficits in force production were likely due to peripheral changes in the muscle, and could include atrophy, architectural adaptations, and alterations in tendon viscoelastic properties, compliance of the series elastic components, or fiber type composition. Six months after ACL reconstruction, quadriceps atrophy was strongly related to deficits in strength of the involved limb(Thomas et al., 2015), while 2-15 years post-surgery, chronic quadriceps weakness was related to peripheral changes in the muscle but not VA.(Krishnan and Williams, 2011)

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Unexpectedly, the deficits in knee extensor RFD between the involved and uninvolved limbs of subjects post-ACL reconstruction closely paralleled the magnitude of the asymmetries in knee extensor MVIC. When normalized to peak strength, the ability to rapidly generate quadriceps force in this population was nearly equal between limbs. In agreement with this finding was the similarity in the rate of quadriceps muscle activation between legs in the early portion of a rapid voluntary contraction. There is strong evidence to suggest that, in healthy people, the ability to rapidly develop quadriceps force is related to the ability to rapidly activate the quadriceps muscles at the initiation of a contraction.(Folland et al., 2014) This is the first known investigation of rapid quadriceps activation in people who have undergone ACL reconstruction. Previous investigations have reported deficits in involved leg rapid quadriceps activation that were strongly related to the ability to rapidly generate knee extensor torque following arthroscopic knee surgery.(Cobian et al., 2015b)

In the group that participated in this study, side to side asymmetries in rapid voluntary force development measured from the onset of contraction appear to be primarily controlled by the intrinsic contractile properties of the quadriceps muscles. Evaluating changes in rapid force development in consecutive epochs allows for more specific determinations regarding the neuromuscular determinants of RFD.(Tillin et al., 2010) Although there were no between limb differences in quadriceps activation during the initial period of the contraction, there was a significant side-to-side asymmetry in VM activation from 100-200 ms after the onset of contraction. This finding in is concert with a > 36% deficit in force production between 100 and 200 ms, nearly 17% greater than the corresponding deficits in maximal strength. As expected, $\text{QUAD}_{100\text{-}200}$ was strongly positively correlated with knee extensor $\text{RFD}_{100\text{-}200}$ ($r = .558$, $p =.025$). Thus, it may not be the initial burst of muscle activation, but rather the inability to properly

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regulate and or maintain continuous increases in quadriceps activation that limits RFD in this population.(Williams et al., 2003)

Voluntary activation testing with a triplet-superimposition technique provides a method of assessing the completeness of motor unit recruitment during a maximal voluntary contraction.(Shield and Zhou, 2004) Numerous investigations have reported side-to-side asymmetries in voluntary quadriceps activation after ACL reconstruction.(Hart et al., 2010b) Although involved limb quadriceps activation averaged 80.4% in this population, mean VA of the uninvolved leg was similar, which indicates that subjects in this study may be presenting with bilateral deficits in quadriceps neuromuscular function.(Lepley et al., 2015, Urbach et al., 1999)

Conversely, quadriceps activation assessed by both surface EMG and twitch interpolation technique can vary as a function of knee joint angle, and thus, muscle length.(Becker and Awiszus, 2001, Krishnan and Theuerkauf, 2015, Kubo et al., 2004) In the current study, an angle of 60 degrees could have contributed to the lower VA values observed bilaterally. Future investigations should consider assessing quadriceps RFD in ACL subjects through a range of knee joint angles.

Although the lack of a concurrently tested control group prohibits direct comparisons with healthy individuals, quadriceps voluntary activation has been reported to typically be in the range of 95% in young, healthy adults used as matching controls in other studies.(Hart et al., 2010b) Bilateral quadriceps dysfunction and activation deficit following ACL reconstruction is thought to be controlled by central mechanisms.(Lepley et al., 2015) If quadriceps motor unit recruitment and firing rate are inhibited bilaterally, we would expect to see reduced quadriceps force production and RFD of both limbs. We previously investigated rapid knee extensor torque development in a group of individuals undergoing arthroscopic partial meniscectomy (APM).

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Though there were methodological differences between these studies, normalized maximum rate of torque development in the previous study was 11.6 and 12.0% peak voluntary torque/second in the involved and uninvolved limbs prior to APM, compared to 11.1 and 11.0% peak force/second in the current study. Thus, normalized RFD in the ACL reconstruction group was lower in both limbs, despite the subject population being over 15 years younger, and RFD efforts being performed at 60 degrees of knee flexion, which has been shown to produce greater RFD values than when measured at 90 degrees of knee flexion.(de Ruiter et al., 2004a)

Peak knee extensor force production was significantly lower in the involved limb and paralleled the deficits in rapid force development. Peak force elicited by octet stimulation was variable between subjects but the LSI was 89.1%, which is comparable to the voluntary knee extensor MVIC LSI of 84.4% in the group of subjects who were able to tolerate the stimulation protocol. In addition, involved leg voluntary knee extensor peak force and octet peak force LSI values were strongly positively correlated.

In this study, we calculated knee joint biomechanics during walking, stepping down, and hopping. The time to develop knee extension torque during these activities was typically in the range of 100 – 400 ms. Thus, inability to develop quadriceps contractile force over the later phase of a rapidly voluntary contraction (i.e. from 100 ms on) could result in limited functional performance of these activities. It may also help to explain why leg press PP and PA deficits were greater in the involved limb, which typically occurred around 100-150 ms (peak acceleration) and 200-300 ms (peak power) after the initiation of force development.

Mean time from surgery for the subjects in this study was almost 10 months. It is possible that greater deficits in neural mechanisms moderating rapid voluntary contractions would have been observed in people that had more recent surgery. Alterations in quadriceps

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dyskinesia and muscle activation patterns have been reported 3 months following surgery (Drechsler et al., 2006), while at 6 months after surgery improved muscle specificity was noted in nearly all lower extremity muscles in a group of high level subjects.(Williams et al., 2005b) Interestingly, Williams et al. reported that post-surgery, the only muscle of the involved limb that had significantly lower specificity than in the uninvolved limb was the vastus medialis, which is consistent with the findings of the current investigation that VM activation from 100-200 ms after onset of a rapid voluntary contraction was significantly lower in the involved limb. Two previous investigations that reported RFD deficits to be greater than strength deficits following ACLR tested subjects at 4 and 6 months post-ACL reconstruction.(Angelozzi et al., 2012, Knezevic et al., 2014) In one of these studies, a re-test at 12 months post-surgery demonstrated the deficits in RFD reported 6 months after surgery had since resolved.(Angelozzi et al., 2012) In the current investigation, non-significant but weak negative correlations were found between time from surgery and involved limb EMD of the VL, RF, and VM (r = -.389, -.347, and -.272, respectively). In addition, a non-significant but moderately positive correlation was found between time form surgery and involved limb VA (r = .473, p = .103). Thus, perhaps the expected asymmetries in rapid quadriceps neural activation following ACL reconstruction may be, for the most part, normalized to the uninvolved limb by 6-12 months post-surgery.

Despite similar LSI values of rapid and maximal force development, RFD and closed chain power and acceleration were strongly correlated with both movement biomechanics and patient-based outcomes scores. RFD and power/acceleration were strongly related to knee joint kinetics during walking over level ground, while peak strength was not. Conversely, leg press strength was the variable most strongly correlated with performance of single leg vertical hops. Both single leg hop distance and hop height were correlated with knee extensor RFD but not

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with knee extensor MVIC LSI values, indicating that the ability to rapidly produce knee extensor force is an important factor in normalizing hop performance. Another interesting finding was that PP, PA, and RFD were correlated with asymmetries in knee joint biomechanics during walking over level ground, while LP 1RM and KE MVIC were not. During walking, the peak knee extensor torque requirement of the uninvolved limb in the initial 25% of stance phase was only approximately 40% of the torque requirement during the step down task. Thus, it is logical that limitations in rapid force development may inhibit normal performance of this activity to a greater extent than limitations in maximal force development.

Leg press strength, power, and acceleration were particularly strongly correlated with knee joint kinetics and hop performance. The dynamic leg press task is functionally more comparable to the action of the leg when performing typical weight bearing activities, and particularly in relation to hopping. The coordinated pattern of muscle activity is in some contrast to the action of the quadriceps or hamstrings during open chain isometric knee flexion or extension. Between limb asymmetries in knee extensor MVIC were greater than the deficits in LP 1 RM. All but two subjects had greater deficits in knee extensor MVIC than LP 1RM, and they were the only two subjects to produce greater knee extensor MVIC with the involved leg. This is in agreement with our previous findings in patients who recently underwent APM – recovery of isolated quadriceps strength was less complete than recovery of leg press strength.(Cobian et al., 2015a) This is most likely due to the contributions of other lower extremity muscles in performance of the leg press. Interestingly, peak power and peak acceleration LSI values were similar to the LSI values for knee extensor RFD variables, and were significantly greater than deficits in leg press strength. The quadriceps may contribute more to the initial phase of the leg press action than the knee flexors, hip extensors, and

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plantarflexors, which would result in greater deficits in power/acceleration than LP strength. It is also possible subjects may have been hesitant to rapidly extend the knee to near full extension. Regardless, the inability to develop leg press force, power, and acceleration was strongly related to abnormal movement biomechanics and limitations in hopping performance in this population.

As clinical measurements, single leg hop height and hop distance can provide valuable characterizations of leg muscle performance, as both height and distance were very strongly positively related to asymmetries in closed chain leg press strength and power and strongly positively related to asymmetries in knee extensor RFD. The single leg VH test appears to be a more sensitive measure of recovery following ACL reconstruction, as not a single subject produced an LSI value of ≥ 100%. It is also interesting to note that there were significant differences between the LSI values of knee joint kinetics and hop height or distance, indicating that subjects may have been using alternative movement biomechanics to maximize performance in SL hopping with the involved limb. Previous investigations have noted that people post-ACL reconstruction perform single leg vertical hops with reduced knee joint moments and quadriceps activation, but maintain hop height by utilizing greater ankle and hip joint moments and greater hip extensor activity.(Ernst et al., 2000, Nyland et al., 2010) It is important to note that the instructions provided to subjects in this investigation were slightly modified from the typical clinical instructions to emphasize the takeoff portion of the movement, and the results should be interpreted with proper discretion.

There are potential limitations in this investigation which warrant discussion. The electrical stimulation protocol utilized in this study was designed to minimize exposure to any noxious stimuli, but despite these efforts, five subjects had difficulty tolerating the stimulus and thus recorded partially incomplete datasets. The lack of a complete stimulus profile for these

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subjects is a limitation to the strength of the conclusions regarding the data gained from the evoked octet contractions and VA analysis. In addition, there is some conjecture regarding the proper application and execution of the twitch-interpolation technique (Shield and Zhou, 2004, Taylor, 2009), though the protocol used in this study addresses many of those concerns.

Subjects in this study underwent reconstruction performed by one of five orthopaedic surgeons. Variations in the surgical technique and post-operative procedures could have contributed to variability within the data. Although all subjects followed the same post-operative rehabilitation protocol, exercise selection and dosage was not controlled. Differences in technique or philosophy among physical therapists could have influenced the results.

Future investigations should explore these concepts in additional populations, particularly those with more recent surgery than the subjects in this study, to determine how neuromuscular factors related to rapid muscle activation and force development adapt over time. Based on the strength of the relationships between RFD, power, movement biomechanics, and subjective knee function, training interventions which target rapid muscle activation or retraining the system to be able to appropriately modulate force should be explored. Earlier normalization of lower extremity biomechanics and neuromuscular function could improve long-term knee-related quality of life, which would be a significant development.

## Conclusions

People roughly 10 months post-ACL reconstruction present with significant involved limb deficits in the ability to rapidly produce knee extensor force, but this is primarily due to the intrinsic musculotendinous factors and not to the ability to rapidly activate the quadriceps muscles at the initiation of contraction. Both knee extensor strength and RFD are significantly

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correlated with function and outcomes after ACL reconstruction. Side to side deficits in peak closed chain leg press power and acceleration are significantly greater than deficits in leg press strength, and closed chain strength, power, and acceleration are strongly correlated with knee joint biomechanics in performance of walking, stepping, and hopping activities, as well as subjective knee function.

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Figure 5.1: Subject positioned on the instrumented pneumatic leg press device for assessing lower extremity strength and power.

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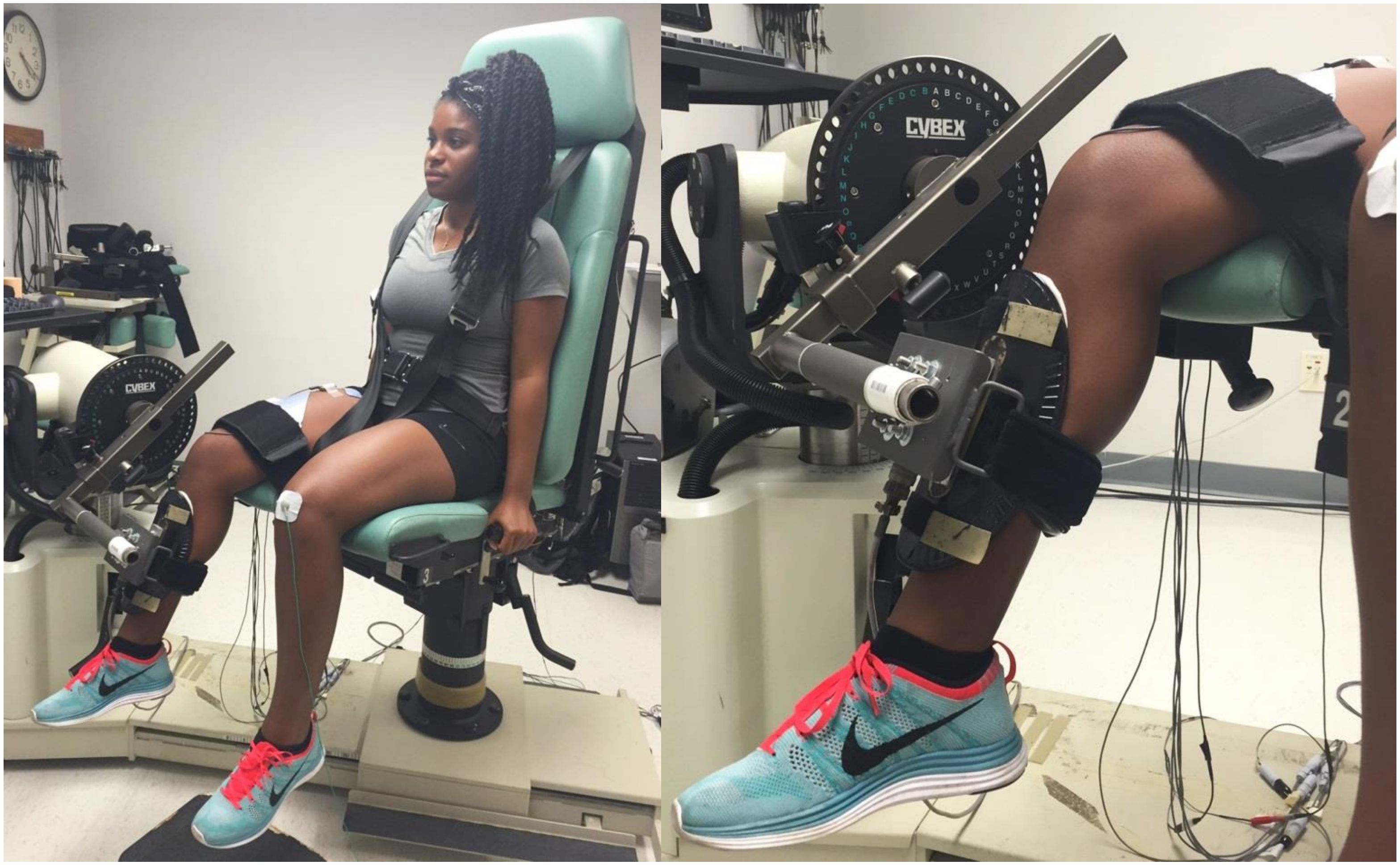

Figure 5.2: Subject positioned in 60 degrees of knee flexion for isometric testing of quadriceps muscle contractile properties, strength, activation, and RFD.

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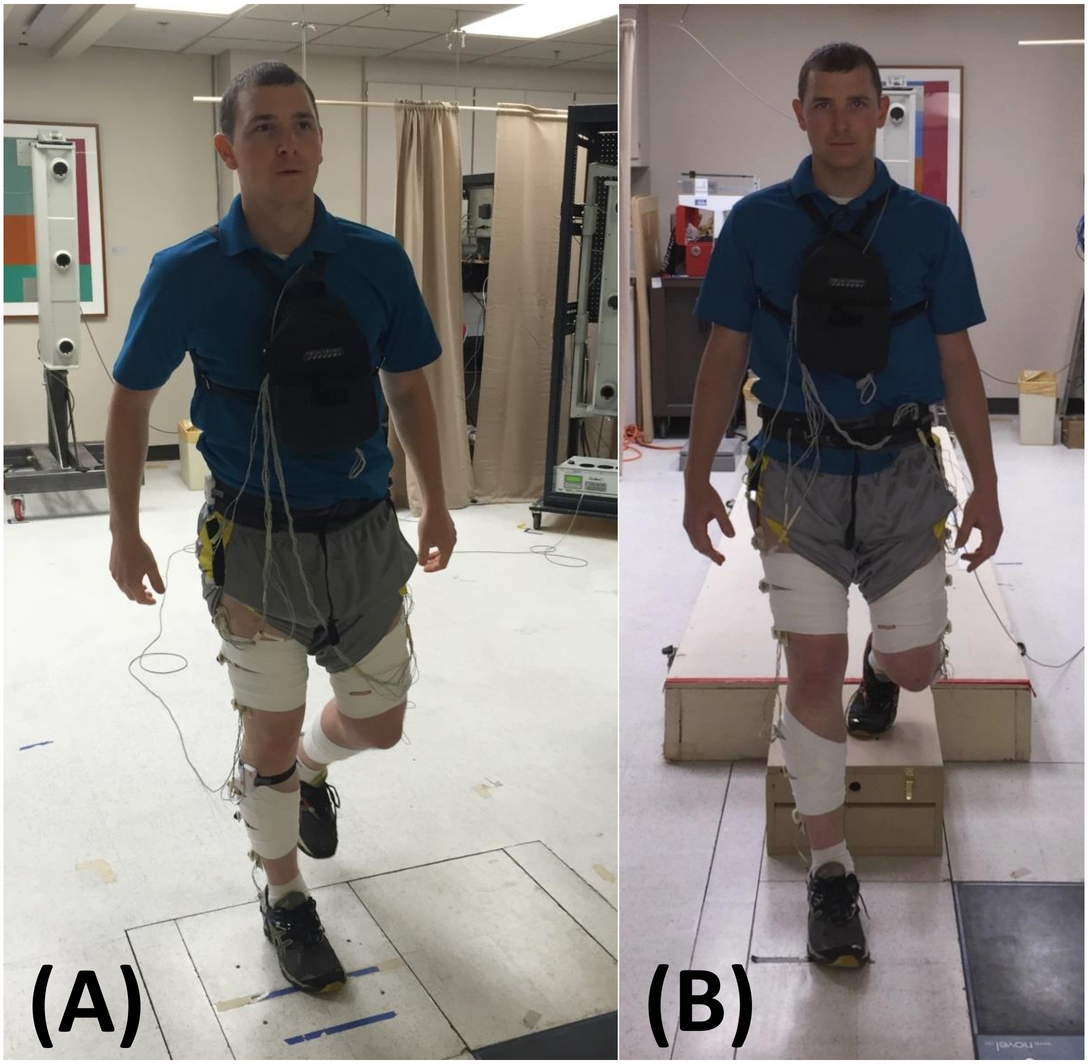

Figure 5.3: Subject performing a single leg vertical hop (A) and walk and step down trial (B) while a motion capture system records the three dimensional coordinates of infrared emitting diodes secured to the pelvis and lower extremities.

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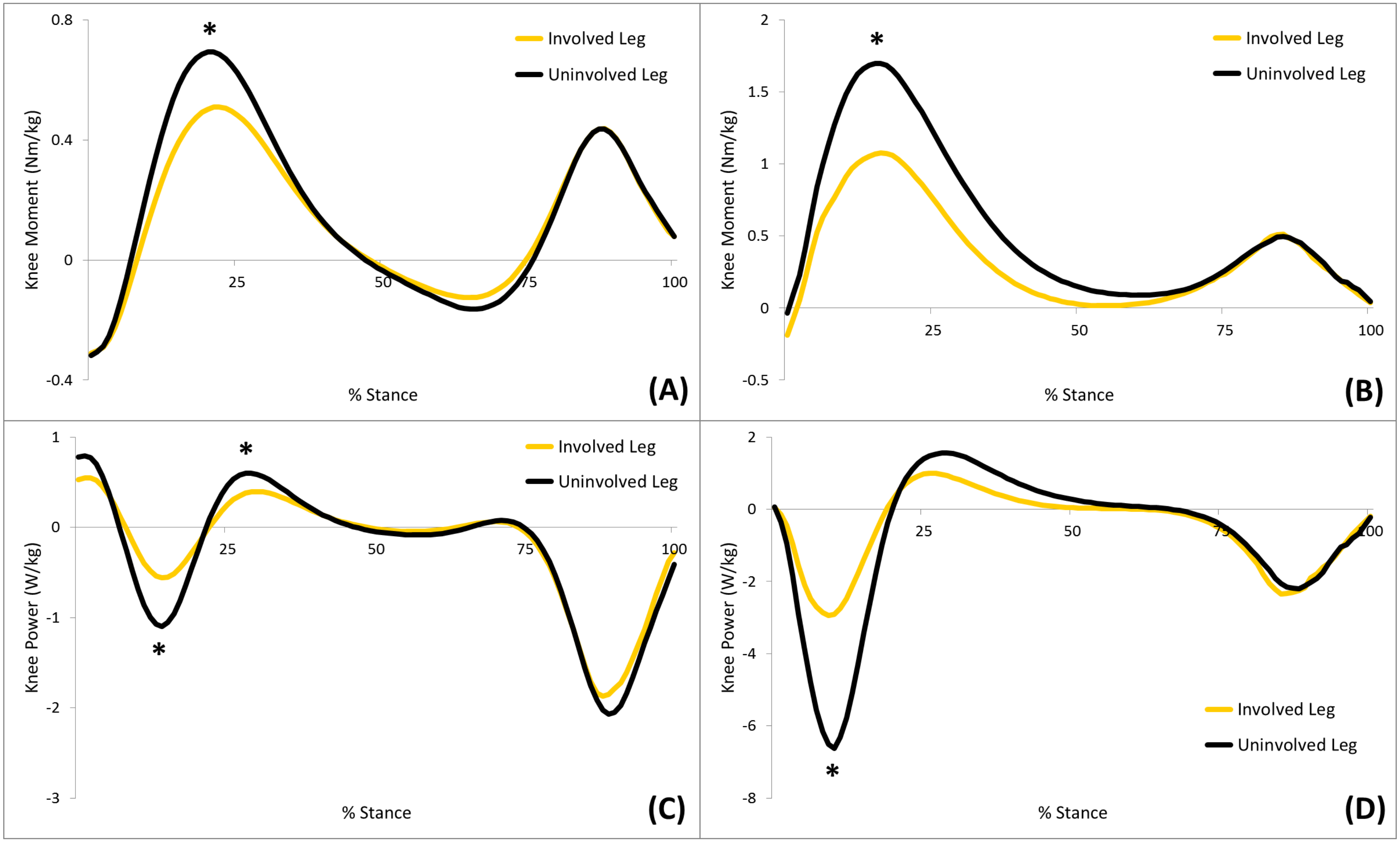

Figure 5.4: Ensemble averaged knee joint internal moments (positive values are extension) during the stance phase of walking (A) and stepping down with the leading leg (B) of the involved and uninvolved limbs. Knee joint powers (negative values are energy absorption) during the stance phase of walking (C) and stepping down with the leading leg (D) of the involved and uninvolved limbs. * represent significant differences in peak moments and powers between the involved and uninvolved limbs ($p < .05$).

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Table 5.1: Subject demographics

| Subject Characteristics | Mean (SD) | Range |
|---|---|---|
| Age | 26.9 (6.8) | 18 - 40 |
| Height (m) | 1.72 (0.09) | 1.59 - 1.89 |
| Mass (kg) | 80.0 (14.4) | 59.2 - 105.3 |
| BMI | 26.9 (4.4) | 19.2 - 34.9 |
| Physical Therapy Visits | 24.5 (8.7)* | 12 - 38 |
| Time from Injury to Surgery (days) | 39.3 (31.2)[#] | 17 - 120 |
| Marx Activity Scale | 10.6 (3.4) | 5 - 16 |
| Global Knee Rating Scale | 82.6 (9.9) | 60 - 100 |
| ACL - RSI | 50.3 (18.8) | 14.2 - 80 |
| IKDC | 78.2 (11.6) | 50.6 - 95.4 |
| KOOS Sports/Rec | 63.9 (21.4) | 10 - 90 |
| KOOS4 | 73.0 (12.7) | 37.1 - 95.0 |
| TSK-11 | 20.6 (5.8) | 11 - 30 |
| PAIN-VAS (mm)[+] | 10.0 (15.3) | 0 - 62 |
| Sex | 9 Female, 9 Male | |
| Surgical Limb | 8 Left, 10 Right | |
| Injury Mechanism | 13 Noncontact, 3 Contact, 2 Unknown | |
| With Concomitant Meniscal Tear | 10 | |
| Graft | 6 BPTB, 12 STG | |

*This information was only available for 16/18 subjects

[#] Two significant outliers (210 and 330 days) were excluded from this calculation

[+] As assessed by a 100 mm PAIN-VAS scale completed following the walk and step down task

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Table 5.2: Clinical characteristics of the study population

| **Clinical Measurements** | **Uninvolved Mean (SD)** | **Involved Mean (SD)** |
|---|---|---|
| Leg Circumference at Knee Joint Line (cm) | 37.5 (2.3) | 37.4 (2.4) |
| Leg Circumference 10 cm proximal to base of patella (cm) | 50.5 (4.8) | 49.1 (4.7)* |
| Knee Extension ROM (degrees) | 3.2 (3.6) | 1.3 (1.9)* |
| Knee Flexion ROM (degrees) | 141.9 (9.6) | 137.5 (9.9)* |
| KT 2000™ Manual Maximum Test (mm) | 6.8 (1.6) | 8.9 (2.3)* |

For knee extension ROM, positive values represent hyperextension.
*significant difference between involved and uninvolved mean value (p < .05)

Table 5.3: Voluntary knee extensor strength and RFD

| **Variable** | Uninvolved | Involved | LSI | ES | p Value |
|---|---|---|---|---|---|
| MVIC (N) | 834.4 ± 197.1 | 671.4 ± 199.2 | 81.1% | 0.82 | ***<.001*** |
| NORM MVIC (N/kg) | 10.6 ± 2.5 | 8.6 ± 2.5 | 81.1% | 0.82 | ***<.001*** |
| MRFD (N/s) | 9126.3 ± 3010.8 | 7408.5 ± 2874.1 | 81.1% | 0.58 | ***0.001*** |
| MRFD$_{NORM}$ (%MVIC/s) | 11.1 ± 3.2 | 11.0 ± 2.4 | 98.9% | 0.04 | 0.882 |
| RFD$_{20\text{-}80}$ (Nm/s) | 4685.5 ± 2403.2 | 3888.1 ± 2283.3 | 83.0% | 0.34 | ***0.032*** |
| F$_{0\text{-}50}$ (N) | 164.1 ± 62.1 | 133.5 ± 64.0 | 81.3% | 0.48 | 0.066 |
| F$_{50\text{-}100}$ (N) | 273.5 ± 115.4 | 240.0 ± 133.8 | 87.7% | 0.29 | 0.110 |
| F$_{100\text{-}200}$ (N) | 203.3 ± 74.1 | 129.8 ± 37.9 | 63.8% | 1.25 | ***0.001*** |
| F$_{50}$ (% of MVIC) | 20.7 ± 9.6% | 19.9 ± 7.4% | 96.5% | 0.09 | 0.691 |
| F$_{100}$ (% of MVIC) | 52.2 ± 13.1% | 53.1 ± 14.3% | 101.8% | -0.07 | 0.719 |
| F$_{200}$ (% of MVIC) | 70.6 ± 14.3% | 66.6 ± 15.3% | 96.5% | 0.27 | 0.119 |
| FTI$_{0\text{-}50}$ (N*s) | 2.56 ± 1.0 | 2.06 ± 1.2 | 80.5% | 0.44 | 0.160 |
| FTI$_{0\text{-}100}$ (N*s) | 17.1 ± 4.5 | 14.3 ± 6.1 | 83.2% | 0.54 | ***0.041*** |
| FTI$_{0\text{-}200}$ (N*s) | 68.4 ± 16.3 | 54.8 ± 21.5 | 80.2% | 0.71 | ***0.003*** |

**Abbreviations:** MVIC, maximum voluntary isometric contraction; NORM MVIC, MVIC normalized to mass in kg; MRFD, maximum rate of force development; MRFD$_{NORM}$, MRFD normalized to MVIC; RFD$_{20\text{-}80}$, rate of force development from 20 to 80% of peak force; F$_{0\text{-}50/50\text{-}100/100\text{-}200}$, increase in force in consecutive windows between 0 and 50/50 and 100/100 and 200 ms; F$_{50/100/200}$, force at 50/100/200 ms (expressed as % of MVIC); FTI$_{0\text{-}50/100/200}$, force time integral from 0-50/0-100/0-200 ms; LSI, Limb Symmetry Index [(Uninvolved/Involved) *100]; ES, Effect Size (Cohen's d).

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Table 5.4: Voluntary knee flexor strength and RFD

| Variable | Uninvolved | Involved | LSI | ES | p Value |
|---|---|---|---|---|---|
| MVIC (N) | 363.9 ± 122.3 | 347.0 ± 115.7 | 95.4% | 0.14 | 0.318 |
| NORM MVIC (N/kg) | 4.6 ± 1.3 | 4.4 ± 1.3 | 95.4% | 0.15 | 0.319 |
| MRFD (N/s) | 4525.9 ± 2177.1 | 4349.4 ± 1686.8 | 96.1% | 0.09 | 0.425 |
| MRFD$_{NORM}$ (%MVIC/s) | 12.3 ± 3.8 | 12.7 ± 3.1 | 103.2% | -0.12 | 0.598 |
| RFD$_{20\text{-}80}$ (Nm/s) | 2662.9 ± 1646.5 | 2485.6 ± 1285.4 | 93.3% | 0.12 | 0.515 |
| F$_{0\text{-}50}$ (N) | 40.7 ± 21.3 | 41.1 ± 16.2 | 101.1% | -0.02 | 0.905 |
| F$_{50\text{-}100}$ (N) | 100.2 ± 68.3 | 83.6 ± 43.9 | 83.4% | 0.29 | 0.155 |
| F$_{100\text{-}200}$ (N) | 143.4 ± 55.6 | 145.6 ± 55.9 | 101.5% | -0.04 | 0.843 |
| F$_{50}$ (% of MVIC) | 11.3 ± 5.1% | 12.3 ± 4.9% | 108.5% | -0.20 | 0.506 |
| F$_{100}$ (% of MVIC) | 37.8 ± 15.1% | 33.4 ± 10.2% | 88.3% | 0.34 | 0.144 |
| F$_{200}$ (% of MVIC) | 76.1 ± 10.5% | 73.0 ± 8.4% | 95.9% | 0.33 | 0.260 |
| FTI$_{0\text{-}50}$ (N*s) | 0.89 ± 0.5 | 0.96 ± 0.3 | 107.4% | -0.17 | 0.497 |
| FTI$_{0\text{-}100}$ (N*s) | 4.9 ± 2.6 | 4.4 ± 1.8 | 89.5% | 0.22 | 0.237 |
| FTI$_{0\text{-}200}$ (N*s) | 27.7 ± 9.7 | 26.2 ± 9.4 | 94.7% | 0.16 | 0.209 |

**Abbreviations:** MVIC, maximum voluntary isometric contraction; NORM MVIC, MVIC normalized to mass in kg; MRFD, maximum rate of force development; MRFD$_{NORM}$, MRFD normalized to MVIC; RFD$_{20\text{-}80}$, rate of force development from 20 to 80% of peak force; F$_{0\text{-}50/50\text{-}100/100\text{-}200}$, increase in force in consecutive windows between 0 and 50/50 and 100/100 and 200 ms; F$_{50/100/200}$, force at 50/100/200 ms (expressed as % of MVIC); FTI$_{0\text{-}50/100/200}$, force time integral from 0-50/0-100/0-200 ms; LSI, Limb Symmetry Index [(Uninvolved/Involved) *100]; ES, Effect Size (Cohen's d).

Table 5.5: Evoked knee extensor strength, RFD, and Voluntary Activation

| Variable | Uninvolved | Involved | LSI | p Value |
|---|---|---|---|---|
| Octet Peak Force (N) | 513.6 ± 96.8 | 457.8 ± 99.2 | 89.1% | 0.068 |
| Octet MRFD (N/s) | 11691.4 ± 2362.1 | 10638.6 ± 2929.1 | 91.0% | 0.098 |
| Octet MRFD$_{NORM}$ | 23.0 ± 4.3 | 23.4 ± 4.3 | 101.5% | 0.830 |
| Vol/Octet MRFD$_{NORM}$ (%) | 51.0 ± 20.0 | 50.9 ± 16.4 | 100.0% | 0.969 |
| Voluntary Activation (%) | 79.5 ± 12.5 | 80.4 ± 12.0 | 101.2% | 0.834 |

**Abbreviations:** MRFD, maximum rate of force development; MRFD$_{NORM}$, MRFD normalized to octet peak force; Vol/Octet MRFD$_{NORM}$, normalized voluntary MRFD/normalized octet MRFD; LSI, Limb Symmetry Index [(Uninvolved/Involved) *100].

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Table 5.6: Neuromuscular activation characteristics of the quadriceps and hamstrings muscles during rapid voluntary efforts

| **Variable** | Uninvolved | Involved | LSI | p Value |
|---|---|---|---|---|
| QUAD$_{0-50}$ (%EMG$_{MVIC}$) | 58.7 ± 24.0% | 65.2 ± 25.3% | 111.0% | 0.250 |
| QUAD$_{0-100}$ (%EMG$_{MVIC}$) | 84.9 ± 25.6% | 83.9 ± 28.7% | 98.8% | 0.883 |
| QUAD$_{0-200}$ (%EMG$_{MVIC}$) | 81.6 ± 20.7% | 77.3 ± 22.3% | 94.8% | 0.330 |
| QUAD$_{50-100}$ (%EMG$_{MVIC}$) | 103.3 ± 33.3% | 96.6 ± 33.4% | 93.6% | 0.454 |
| QUAD$_{100-200}$ (%EMG$_{MVIC}$) | 78.9 ± 19.6% | 71.7 ± 22.0% | 90.9% | 0.055 |
| QUAD EMD (ms) | 48.3 ± 13.3 | 46.8 ± 13.2 | 103.3% | 0.658 |
| QUAD TRT (ms) | 370.2 ± 32.0 | 361.9 ± 38.0 | 102.3% | 0.220 |
| HS$_{0-50}$ (%EMG$_{MVIC}$) | 47.4 ± 20.9% | 49.6 ± 25.9% | 104.6% | 0.745 |
| HS$_{0-100}$ (%EMG$_{MVIC}$) | 69.8 ± 24.8% | 69.9 ± 24.5% | 100.1% | 0.988 |
| HS$_{0-200}$ (%EMG$_{MVIC}$) | 78.4 ± 19.7% | 76.4 ± 18.0% | 97.5% | 0.738 |
| HS$_{50-100}$ (%EMG$_{MVIC}$) | 86.6 ± 35.1% | 84.5 ± 29.4% | 97.5% | 0.791 |
| HS$_{100-200}$ (%EMG$_{MVIC}$) | 83.9 ± 17.7% | 81.6 ± 16.8% | 97.2% | 0.722 |
| HS EMD (ms) | 36.5 ± 12.4 | 35.9 ± 13.7 | 100.8% | 0.695 |
| HS TRT (ms) | 342.2 ± 39.9 | 339.4 ± 45.1 | 100.8% | 0.686 |

**Abbreviations:** QUAD$_{0-50/0-100/0-200}$, root mean square (RMS) amplitude of the quadriceps combined mean value (vastus lateralis + rectus femoris + vastus medialis) from 0 to 50/100/200 ms; HS$_{0-50/0-100/0-200}$, RMS amplitude of the hamstrings combined mean value (semitendinosus + biceps femoris) from 0 to 50/100/200 ms; EMD, electromechanical delay (time difference between EMG onset and force onset); TRT, total reaction time (time difference between audio signal and force onset); LSI, Limb Symmetry Index [(Uninvolved/Involved) *100].

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Table 5.7: Leg Press strength, power, and acceleration

| **Variable** | Uninvolved | Involved | LSI | ES | p Value |
|---|---|---|---|---|---|
| LP 1RM (N/kg) | 8.3 ± 1.7 | 7.4 ± 2.3 | 88.3% | 0.47 | ***0.002*** |
| $PP_{40}$ (W/kg) | 12.5 ± 2.8 | 10.4 ± 3.3 | *83.2% | 0.68 | ***<.001*** |
| $PP_{70}$ (W/kg) | 13.0 ± 2.4 | 10.8 ± 2.9 | 83.1% | 0.82 | ***<.001*** |
| $PA_{40}$ (G * N/kg) | 12.8 ± 3.8 | 10.2 ± 4.2 | *79.9% | 0.64 | ***<.001*** |
| $PA_{70}$ (G * N/kg) | 7.4 ± 3.0 | 6.6 ± 3.0 | 88.5% | 0.29 | ***0.004*** |

**Abbreviations:** LP 1RM, one repetition maximum leg press strength normalized to body mass (kg); $PP_{40}$, peak power at 40% 1RM resistance; $PP_{70}$, peak power at 70% 1RM resistance; $PA_{40}$, peak acceleration at 40% 1RM resistance; $PA_{70}$, peak acceleration at 70% 1RM resistance; W, watts; G, acceleration in units of gravity; LSI, Limb Symmetry Index [(Uninvolved/Involved) *100]; ES, Effect Size (Cohen's d).

*significant difference between peak power or acceleration LSI and 1RM LSI ($p < .05$)

Table 5.8: Knee joint biomechanics during single leg hopping tasks

| **Variable** | Uninvolved | Involved | LSI | ES | p Value |
|---|---|---|---|---|---|
| VH Peak Knee Extensor Moment (Nm/kg) | 1.94 ± 0.50 | 1.39 ± 0.77 | 68.5% | 0.85 | ***<.001*** |
| VH Peak Knee Power Generation (W/kg) | 10.1 ± 3.7 | 6.4 ± 4.2 | 57.0% | 0.93 | ***<.001*** |
| VH Height (cm) | 15.4 ± 4.2 | 11.4 ± 5.2 | 69.5% | 0.85 | ***<.001*** |
| HFD Peak Knee Extensor Moment (Nm/kg) | 2.7 ± 0.82 | 2.1 ± 1.01 | 74.8% | 0.64 | ***0.001*** |
| HFD Peak Knee Power Generation (W/kg) | 16.9 ± 8.3 | 11.6 ± 7.3 | 68.5% | 0.68 | ***0.006*** |
| HFD Distance (cm) | 159.8 ± 30.8 | 142.5 ± 40.8 | 88.1% | 0.48 | ***0.004*** |

**Abbreviations:** VH, vertical hop; HFD, hop for distance; W, watts.

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Table 5.9: Correlations (Pearson's r) between knee joint biomechanics during walking and step down tasks and strength, power, and RFD variables

| **Mode** | **LSI Values** | Peak Knee Joint Moment (walking) | | Peak Knee Power Absorption (walking) | | Peak Knee Joint Moment (Step Down Leading Limb) | | Peak Knee Joint Moment (Step Down Trailing Limb) | |
|---|---|---|---|---|---|---|---|---|---|
| | | r | p value | r | p value | r | p value | r | p value |
| **Power Leg Press** | LP 1RM | 0.207 | 0.409 | 0.377 | 0.123 | 0.662 | ***0.003*** | 0.707 | ***0.001*** |
| | $PP_{40}$ | 0.389 | 0.111 | 0.544 | ***0.020*** | 0.778 | ***< .001*** | 0.706 | ***0.001*** |
| | $PA_{40}$ | 0.384 | 0.116 | 0.521 | ***0.027*** | 0.808 | ***< .001*** | 0.703 | ***0.001*** |
| **Isometric Knee Extension** | KE MVIC | 0.463 | 0.053 | 0.322 | 0.193 | 0.695 | ***0.001*** | 0.797 | ***< .001*** |
| | KE MRFD | 0.477 | ***0.045*** | 0.603 | ***0.008*** | 0.465 | 0.052 | 0.560 | ***0.016*** |
| | KE $FTI_{0\text{-}200}$ | 0.316 | 0.201 | 0.369 | 0.132 | 0.620 | ***0.006*** | 0.726 | ***0.001*** |

**Abbreviations:** LSI, Limb Symmetry Index [(Uninvolved/Involved) *100]; LP 1RM, one repetition maximum leg press strength normalized to body mass (kg); $PP_{40}$, peak power at 40% 1RM resistance; $PA_{40}$, peak acceleration at 40% 1RM resistance; KE; knee extension, MVIC, maximum voluntary isometric contraction; MRFD, maximum rate of force development; $FTI_{0\text{-}200}$, force time integral from 0-200 ms.

**Note:** LP strength and power variables are highlighted in orange, knee extensor strength and RTD variables are highlighted in gold.

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Table 5.10: Correlations (Pearson's r) between knee joint biomechanics during single leg hopping tasks and strength, power, and RFD variables

| Mode | LSI Values | VH Peak Knee Power | | VH Height | | HFD Peak Knee Power | | HFD Height | |
|---|---|---|---|---|---|---|---|---|---|
| | | r | p value | r | p value | r | p value | r | p value |
| **Power Leg Press** | LP 1RM | 0.841 | ***< .001*** | 0.771 | ***< .001*** | 0.760 | ***0.001*** | 0.889 | ***< .001*** |
| | $PP_{40}$ | 0.803 | ***< .001*** | 0.715 | ***0.001*** | 0.625 | ***0.013*** | 0.851 | ***< .001*** |
| | $PA_{40}$ | 0.752 | ***0.001*** | 0.710 | ***0.001*** | 0.663 | ***0.007*** | 0.752 | ***0.046*** |
| **Isometric Knee Extension** | KE MVIC | 0.387 | 0.139 | 0.484 | ***0.042*** | 0.293 | 0.289 | 0.441 | 0.067 |
| | KE MRFD | 0.548 | ***0.028*** | 0.594 | ***0.009*** | 0.370 | 0.174 | 0.490 | ***0.039*** |
| | KE $FTI_{0\text{-}200}$ | 0.558 | ***0.025*** | 0.643 | ***0.004*** | 0.611 | ***0.016*** | 0.576 | ***0.012*** |

**Abbreviations:** LSI, Limb Symmetry Index [(Uninvolved/Involved) *100]; LP 1RM, one repetition maximum leg press strength normalized to body mass (kg); $PP_{40}$, peak power at 40% 1RM resistance; $PA_{40}$, peak acceleration at 40% 1RM resistance; KE; knee extension, MVIC, maximum voluntary isometric contraction; MRFD, maximum rate of force development; $FTI_{0\text{-}200}$, force time integral from 0-200 ms; VH, vertical hop; HFD, hop for distance.

**Note:** LP strength and power variables are highlighted in orange, knee extensor strength and RTD variables are highlighted in gold.

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Table 5.11: Correlations (Pearson's r) between patient-based outcomes scores and LSI values of strength, power, and RFD variables

| **Mode** | **LSI Values** | GKRS | | ACL-RSI | | IKDC | | KOOS Sports/Rec | | KOOS4 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | r | p value | r | p value | r | p value | r | p value | r | p value |
| **Power Leg Press** | LP 1RM | 0.585 | ***0.011*** | 0.477 | ***0.045*** | 0.725 | ***0.001*** | 0.663 | ***0.003*** | 0.657 | ***0.003*** |
| | PP$_{40}$ | 0.537 | ***0.022*** | 0.442 | 0.067 | 0.663 | ***0.003*** | 0.552 | ***0.018*** | 0.627 | ***0.005*** |
| | PA$_{40}$ | 0.521 | ***0.027*** | 0.515 | ***0.029*** | 0.609 | ***0.007*** | 0.624 | ***0.006*** | 0.623 | ***0.006*** |
| **Isometric Knee Extension** | KE MVIC | 0.248 | 0.322 | 0.404 | 0.096 | 0.452 | 0.060 | 0.368 | 0.133 | 0.421 | 0.082 |
| | KE RFD$_{20\text{-}80}$ | 0.292 | 0.239 | 0.273 | 0.272 | 0.548 | ***0.019*** | 0.605 | ***0.008*** | 0.669 | ***0.002*** |
| | KE FTI$_{0\text{-}200}$ | 0.238 | 0.341 | 0.336 | 0.173 | 0.400 | 0.100 | 0.592 | ***0.010*** | 0.482 | ***0.043*** |

**Abbreviations:** LSI, Limb Symmetry Index [(Uninvolved/Involved) *100]; LP 1RM, one repetition maximum leg press strength normalized to body mass (kg); PP$_{40}$, peak power at 40% 1RM resistance; PA$_{40}$, peak acceleration at 40% 1RM resistance; KE; knee extension, MVIC, maximum voluntary isometric contraction; RFD$_{20\text{-}80}$, rate of force development from 20 to 80% of peak force; FTI$_{0\text{-}200}$, force time integral from 0-200 ms; GKRS, Global Knee Rating Scale; ACL-RSI, ACL Return to Sport after Injury scale; IKDC, International Knee Documentation Committee Subjective Knee Evaluation form; KOOS, Knee Injury and Osteoarthritis Outcome Score.

**Note:** LP strength and power variables are highlighted in orange, knee extensor strength and RTD variables are highlighted in gold.

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# CHAPTER 6

# SUMMARY

The collective goal of this body of work was to assess rapid force production, muscle activation, and lower extremity power in people undergoing arthroscopic knee surgery to explore the neuromuscular factors contributing to lower extremity muscle performance and assess the functional implications of these measures as they relate to movement biomechanics and knee related quality of life. The findings presented in this compilation help to advance our understanding of the neuromuscular response to knee joint trauma, have clinical implications related to the design and dosage of therapeutic intervention and exercise prescription, and set the table for future investigations in this domain.

## Knee Extensor Rate of Torque Development after Arthroscopic Partial Meniscectomy

The initial project in this collection was to evaluate knee extensor RTD before and early after arthroscopic partial meniscectomy (APM) and investigate the neuromuscular factors contributing to RTD in this population. To the best of the author's knowledge, this is the first study of its kind in patients undergoing knee surgery. Subjects completed tests of quadriceps speed, strength, and function before surgery and at 2 weeks and 5 weeks after surgery with each leg. The testing protocol included voluntary isometric knee extension RTD contractions (kicking out as fast and as hard as possible), quadriceps strength and activation testing, evoked contractions, MRI evaluation of quadriceps muscle volume, and patient-based outcomes measures. Based on preliminary data and the existing literature regarding quadriceps neuromuscular dysfunction following knee surgery, the following hypotheses were postulated:

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**Hypothesis 2.1:** Patients undergoing APM will present with significant side to side asymmetries in the ability to rapidly produce knee extensor torque at 2 and 5 weeks after surgery.

*Supported:* Subjects recorded knee extensor RTD deficits of 25-30% in the involved limb at 2 weeks post-surgery, and 20-25% at 5 weeks post-surgery. These deficits were greater than the deficits in peak strength at each interval (17% and 11%, respectively). Deficits in RTD variables normalized to peak strength ranged from 10 to 15%, indicating that factors beyond the maximum force generating capacity of the quadriceps contributed to these deficits.

**Hypothesis 2.2:** Patients undergoing APM will present with side to side asymmetries in quadriceps neural activation in the early period of rapid voluntary efforts. The deficits in voluntary neural activation are expected to parallel the deficits in rapid voluntary torque production.

*Supported:* At 2 weeks post-surgery, there were significant between limb deficits (23 – 35%) in vastus lateralis and vastus medialis activation during the initial 200 ms of voluntary knee extensor RTD efforts. At 5 weeks post-surgery, the side-to-side asymmetries were reduced (10-20% differences between limbs), and only the difference in vastus lateralis activation from 0 to 200 ms was significant. Voluntary activation (assessed by a modified interpolated twitch techniques) was similar between limbs after surgery (asymmetries of 2-4%). However, there were 10 to 15% differences in the ratio of voluntary RTD to evoked RTD, which, in concert with deficits in rapid quadriceps activation during voluntary RTD trials, suggests that impaired centrally mediated neural

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function (related to the ability to rapidly activate the quadriceps) may have inhibited voluntary RTD in the involved limb of this population.

**Hypothesis 2.3:** RTD will be more closely related to subjective knee function than measures of maximal voluntary strength. It is expected that improvements or deficits in the ability to rapidly develop knee extensor torque will be associated with positive or negative changes in self-reported knee function.

*Supported:* KOOS4 and KOOS Sports-Rec scores were significantly correlated with deficits in knee extensor RTD but not with peak strength or quadriceps volume. Improvements in voluntary knee extensor RTD of the involved limb between 2 and 5 weeks post-surgery were significantly positively correlated with increases in the KOOS Sports-Rec scores in the same time period. No other correlations between changes in outcomes scores and muscle performance measurements were found. WOMET scores were negatively correlated with deficits in RTD and strength, but these correlations did not reach significance.

## Closed Kinetic Chain Lower Extremity Power and Neuromuscular Performance after Arthroscopic Partial Meniscectomy

The purpose of this study was to assess leg press (LP) power and isometric knee extensor RTD before and after APM and evaluate the relationships between open and closed chain characterizations of strength, power, quadriceps neuromuscular performance, and patient reported outcomes. Subjects completed tests of lower extremity muscular performance prior to surgery, and at 2 weeks and 5 weeks post-surgery with each leg. Closed chain strength and power was assessed with an instrumented pneumatic LP. Quadriceps muscle function was

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quantified with isometric contractions for strength (MVIC) and speed (RTD), voluntary activation (VA) and evoked contractions assessed muscle recruitment and intrinsic contractile properties. Subjective knee function was assessed with patient-based outcomes measures. Based on pilot investigations and review of published literature, the hypotheses of this study were:

**Hypothesis 3.1:** Patients undergoing APM will have significant side to side asymmetries in LP strength, power, acceleration, and knee extensor RTD after surgery.

*Supported:* Both measures of closed chain power and open chain knee extensor RTD were significantly different between limbs at 2 and 5 weeks after surgery. Both open chain knee extensor strength and LP strength (one repetition maximum) were significantly different at each interval (generally, a side-to-side asymmetry of 10% or less), but deficits in knee extensor RTD and LP peak power/acceleration were greater than strength deficits (power/acceleration: 10-16% difference, knee extensor RTD: 12-25% difference). However, most of the percentage differences between asymmetries in strength and power were not statistically significant.

**Hypothesis 3.2:** LP Power and RTD will be more closely associated with patient reported outcomes than peak strength.

*Partially supported:* Deficits in knee extensor RTD were significantly negatively correlated with KOOS and UCLA Activity scores both before and after surgery. Knee extensor strength (MVIC) was not correlated with KOOS scores and correlations with UCLA scores did not reach significance at any interval. Neither LP power or strength were significantly correlated with subjective knee function either before or after surgery.

**Hypothesis 3.3:** Subjects will demonstrate greater side to side asymmetries in knee extensor RTD than in LP Power after APM.

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*Partially supported:* At 2 weeks post-surgery, knee extensor RTD deficits were greater than asymmetries in LP strength, power, or acceleration. At 5 weeks post-surgery, between limb differences in LP power and acceleration were similar in magnitude to the asymmetries in RTD. Thus, people may use alternative movement patterns with greater contributions from other lower extremity muscle groups to maximize closed chain performance in the presence of significant isolated quadriceps weakness and neuromuscular dysfunction.

## **Performing Faster Quadriceps Contractions in Rehabilitation after Arthroscopic Partial Meniscectomy is Associated with Greater Rapid Torque Development Capacity and Better Patient Reported Outcomes**

In this chapter, the rates of knee extensor torque development and quadriceps activation during high intensity isometric knee extension exercise after APM were evaluated to determine if and how training parameters affect maximum RTD, rapid muscle activation, and patient-based outcomes. Tests of quadriceps strength and RTD were completed prior to surgery and at 2 and 5 weeks after surgery, along with assessment of quadriceps muscle volume (using MRI) and subjective knee function. In guided rehabilitation efforts after APM, subjects completed 10 training sessions (2-3x/week) with self-selected rate of torque increase and quadriceps activation during training. Training data was analyzed to determine training intensity, RTD, and rate of EMG rise for each repetition. Data was compiled and average training parameters (strength and speed) were calculated for each subject.

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**Hypothesis 4.1:** Patients who trained with faster knee extensor rate of torque development (RTD) following APM would be able to produce greater maximal RTD at the post-training test session.

*Supported:* Training RTD was significantly positively correlated with maximal RTD. There were no correlations between pre-surgical maximal RTD and training RTD. The five subjects with the greatest training RTD had significantly greater maximal RTD at 5 weeks post-surgery than the five subjects who recorded the lowest training RTD values. There were no significant differences in maximal RTD between these groups prior to surgery.

**Hypothesis 4.2:** Patients who trained with faster knee extensor RTD following APM would have better patient-based outcomes scores following training.

*Supported:* Training RTD was strongly positively correlated with KOOS and WOMET scores after the training period. In addition, training RTD was strongly positively correlated with change in KOOS scores from pre-surgery to post-rehabilitation. The five subjects with the greatest training RTD had significantly greater KOOS and WOMET scores at 5 weeks post-surgery than the five subjects who recorded the lowest training RTD values. There were no significant differences in KOOS or WOMET scores between these groups prior to surgery.

**Hypothesis 4.3:** Changes in quadriceps muscle strength and volume would be associated with normalized torque integrals (training intensity) but not with training RTD following APM.

*Not supported:* Neither training intensity or training RTD were associated with changes in quadriceps muscle strength and volume. All subjects in this study improved involved

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leg quadriceps strength from pre-surgery to post-rehabilitation. As a whole, quadriceps strength increased by an average of 16.5% while quadriceps volume increased by an average of 5.6%, but there were no correlations between these changes and any of the training parameters that were evaluated.

## Lower Extremity Power and Knee Extensor Rapid Force Development after Anterior Cruciate Ligament Reconstruction

The purpose of the fifth and final chapter of this collection was to characterize rapid lower extremity force development and lower extremity power in the first year after ACL reconstruction to assess the neuromuscular contributions to RFD and power and determine if the ability to rapidly develop lower extremity force or power is related to movement biomechanics and knee-related quality of life. Subjects completed tests of quadriceps and hamstring voluntary strength and RFD testing, tests of quadriceps activation, lower extremity power, and movement biomechanics (walking, stepping down, and single leg hop tests), in addition to patient-rated surveys of knee function. These detailed hypotheses were constructed based on the results of previous investigations, pilot data collected in our laboratory, and current literature/understanding of the neuromuscular consequences of ACL injury and surgery:

**Hypothesis 5.1:** Subjects will demonstrate significant side to side asymmetries in the ratio of voluntary/evoked quadriceps RFD, quadriceps EMG RMS value from onset of contraction to 50 ms, and quadriceps RFD from onset of contraction to 50 ms. Contractile speed properties (assessed with pulse trains of electrical stimulation) will not be significantly different by limb. There will be no side to side asymmetry in quadriceps

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Voluntary Activation failure (assessed by modified triplet-superimposition method during a maximal voluntary contraction and at rest).

*Not Supported:* There were no differences in LSI values of voluntary/evoked quadriceps RFD, quadriceps EMG RMS value from the onset of contraction to 50 ms, and normalized quadriceps RFD from onset of contraction to 50 ms. Although most measures of knee extensor RFD were significantly different between limbs (mean LSI of approximately 80%), this difference was no greater than the deficits in peak quadriceps strength. Although there were no differences in VA, evoked knee extensor peak force was roughly 11% different between limbs, indicating that peripheral differences in the maximal force capacity of the quadriceps was the primary limitation in voluntary RFD. Knee extensor RFD was significantly different between limbs in the later phase of the contraction (100-200 ms), which was paralleled by deficits in rapid quadriceps activation over the same period of time (primarily due to asymmetries in vastus medialis activity)

**Hypothesis 5.2:** Peak knee extensor moments and peak knee power absorption during the stance phase of both walking tasks will be more strongly correlated with RFD and LE power than MVIC or leg press 1RM. Single leg hop height and distance will be more strongly correlated with RFD/power than MVIC/1RM. Subjects with greater deficits in the ability to rapidly produce quadriceps force will demonstrate decreased knee flexion range of motion, peak knee extensor moments, and peak knee power absorption of the involved limb during stance phase in both gait tasks.

*Partially Supported:* Knee extensor RFD was more strongly correlated with knee joint biomechanics during walking and hopping than knee extensor MVIC, but MVIC was more strongly correlated with biomechanics during the step down task. Correlations

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between knee joint biomechanics during hopping and hop performance were also more strongly correlated with knee extensor RFD than MVIC. LP 1RM, power, and acceleration were all strongly correlated with knee joint biomechanics and performance during the step down and hopping tasks. Conversely, only power and acceleration were correlated with knee joint biomechanics during walking. Negative adaptations (decreased peak knee extensor moments and peak knee power absorption) of the involved limb were greater in subjects with greater deficits in isometric knee extensor or LP performance.

**Hypothesis 5.3:** Self-reported knee function after ACL injury and reconstruction will be more strongly correlated with RFD and power than MVIC/1RM. Subjects with greater side to side asymmetries in the ability to rapidly produce force will record lower IKDC, KOOS, ACL-RSI, and TSK-11 scores.

*Partially Supported:* Knee extensor RFD was significantly correlated with IKDC and KOOS values, while there were no significant correlations between knee extensor MVIC and outcomes scores. Conversely, LP 1RM was the variable most strongly correlated with all outcomes scores. LP power and acceleration were also significantly correlated with outcomes scores. Subjects with greater deficits in isometric knee extensor or LP performance recorded lower IKDC, KOOS, GKRS, and ACL-RSI scores..

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## **Summary and Conclusions**

This body of work represents a significant step forward in the understanding of the neuromuscular response to knee joint trauma in regards to rapid quadriceps activation, force production, and lower extremity power. The theoretical basis for this body of work is that rapid muscle activation (and thus, force production), is strongly related to neural factors, and as neuromuscular dysfunction (particularly related to the quadriceps muscle) is a distinguishing characteristic of knee joint injury and surgery, it is logical to conclude that the ability to rapidly activate muscle and develop force may be inhibited. The typical activity levels, movement patterns, and rehabilitation strategies following knee injury and/or surgery serve to amplify the limitations in rapid muscle actions. The potential importance of these concepts relates to the way that people move and use their muscles to accomplish daily and sports activities, which are characterized by very brief periods of rapid muscle activation and relaxation. Ultimately, the goal is to more specifically define the deficits in function related to knee injury or surgery so that better and more specific treatment strategies can be implemented and people can recover from knee joint trauma more quickly and more completely.

The importance of this line of work, from a rehabilitation perspective, is based on the theory that rapid muscle activation or force development is more important than maximal force development to daily function. The results of these studies primarily support this assertion, as RFD was more strongly correlated with patient-based outcomes than peak strength in two populations (APM and ACLR), and more strongly correlated with knee joint biomechanics than peak strength during walking and hopping in patients post-ACL reconstruction. In addition, increases in knee extensor RTD, but not in peak strength, were associated with improvements in subjective knee function following APM. People who trained with a faster self-selected RTD

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recorded no greater increases in quadriceps strength or size than those who trained more slowly, but reported significantly greater patient-based outcomes. These results, coupled with the neuromuscular deficits contributing to rapid force development, provide justification for future training studies that aim to improve rapid muscle activation and force development following knee joint trauma.

It is interesting that the neuromuscular determinants of RFD were significantly different between people who underwent APM and subjects post-ACL reconstruction. In the APM group, involved limb RFD was inhibited to a significantly greater extent than peak force production, and the data obtained from quadriceps surface EMG and electrically evoked quadriceps contractions indicates that this was primarily due to the inability to rapidly voluntarily activate the involved quadriceps muscle. In contrast, subjects who underwent ACL reconstruction presented with no differences in the rates of rapid voluntary quadriceps activation (measured from the onset of contraction) between limbs and asymmetries in absolute RFD were equivalent to differences in the peak force producing capability of the quadriceps muscle. Similar results have been previously recorded in a group of people 2-15 years post-ACL reconstruction.(Krishnan and Williams, 2011) However, deficits in RFD that are greater than the deficits in peak force after ACL reconstruction have been recorded by at least two different groups.(Angelozzi et al., 2012, Knezevic et al., 2014) Neither of these groups performed any measurements of muscle activation, so we cannot be sure what contributed to these deficits, but if peak force development is significantly less inhibited than rapid force development, it is likely that the inability to rapidly activate the agonist muscles plays some role.

The findings of Chapter 5 were somewhat unexpected based on the results of Chapters 2 - 4. There are a number of factors that could contribute to the differences in rapid muscle

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activation and force production between these populations. The time between surgery and testing was drastically different between groups - from 2-5 weeks in the APM group to an average of 10 months (with none less than 6 months) in the ACL reconstruction group. Rapid neuromuscular activation may typically normalize within the first 6 months after surgery. This could be strongly based on the rehabilitation strategy or activity since the surgery. The APM group performed focused quadriceps strengthening exercises according to the post-operative protocol, while the ACL reconstruction group did not follow any specific exercise protocol and the number and frequency of visits varied across the group. The ACL reconstruction group presented with a mean deficit of roughly 20% in knee extensor strength (with only two subjects recording no side-to-side deficit) which is reasonably similar to what has been reported in recent literature reviews.(Lepley, 2015) If subjects in our investigation performed less quadriceps strengthening exercises, and a high volume of balance, proprioception, and “functional” exercises involving more rapid whole body movements (Gruber and Gollhofer, 2004, Gruber et al., 2007), they may have recovered the ability to rapidly fire the quadriceps more completely than quadriceps atrophy and weakness by 6-12 months post-surgery. In addition, the ages, activity levels, and past medical histories of the subjects in the APM group were notably different than the subjects in the ACL reconstruction group. The ACL reconstruction group was younger (approximately 15 years younger than subjects in the APM group) and more active. Due to a variety of neuromuscular factors, with increasing age power and RFD decline more rapidly than strength. Finally, over half of the APM group had undergone at least one previous knee surgery. Cumulative knee trauma can have a compounding effect on neuromuscular dysfunction and may have contributed to the more significant neuromuscular deficits observed in that population.

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The two previous investigations which reported significant knee extensor RFD deficits utilized subjects who were professional athletes in soccer, handball, or judo.(Angelozzi et al., 2012, Knezevic et al., 2014) These populations undergo specific training to optimize sports performance. They are typically high level performers in measurements of strength, power, and rapid force development due to their training specificity, volume, and intensity. The rehabilitation programs followed before and after surgery in this population are likely very specifically regulated. These subject populations are notably dissimilar to the more general populations which were examined in this body of work. These differences may explain why the neuromuscular profiles of people post-ACL reconstruction in this investigation are not in agreement with the previously published literature.

In the context of these results, it is important to note that both strength and RFD are considered important to function. It is clear that quadriceps strength deficits negatively affect function. Either significant quadriceps weakness or significant deficits in quadriceps RFD/rapid muscle activation would be expected to negatively affect function. Going forward, both clinicians and scientists should be aware of the implications, important considerations, and limitations of measuring rapid force development and/or muscle activation, as discussed in the Introduction section.

## Future Research

The studies presented in this body of work set the stage for future investigations of lower extremity power, rapid force development, and rapid muscle activation. In Chapter 5, subjects completed gait, step down, and single leg hopping trials which were used to quantify knee joint biomechanics. To preserve the integrity of the data, we elected not to concurrently measure

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lower extremity muscle activation during these tasks. Quantifying the rate of muscle activation during functional tasks in both healthy and patient populations, as well as how these measurements relate to rapid force development of isolated muscle groups, should be a focus of future investigations.

A substantial number of different variables used to quantify RFD and power were presented in these investigations. It is currently unknown which of these variables are most meaningful to function. Although previous investigations found very early phase RFD variables to be strongly related to function (de Ruiter et al., 2006), the results of these investigations suggest that later phase RFD variables (such as $TTI_{200}$ and $RFD_{20-80}$) are more strongly related to subjective knee function and movement biomechanics than early phase RFD variables, as well as being significantly more reliable.(Buckthorpe et al., 2012) The mechanism of how these muscle performance characteristics specifically contribute to function needs to be explored in greater depth.

The majority of resistance training studies include exercise prescription dosed in total volume (sets x repetitions x load), but exercise tempo is not often controlled or measured. As discussed in this document, the response to training is specific to the training stimulus, which includes the attempted rate of force production. Training studies in which speed of contraction is both specifically dosed and measured are advocated. Specifically, a combined approach of both fast and intense quadriceps contractions early after knee injury or surgery may be the most beneficial in order to address the expected deficits in neuromuscular function and improve outcomes.

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# APPENDIX

## AUTOMATED DETECTION OF SIGNAL ONSETS FOR PROCESSING OF RTD/RFD TRIALS

Tillin et al. recently stated that the “gold standard” method for identifying signal onset is manual/visual identification.(Tillin et al., 2010) The authors base this claim on the use of visual identification as a validation method for forms of automatic detection, and the significant potential for automatic detection threshold methods to result in noticeable latencies in the identification of signal onset. This is a critical issue in obtaining accurate measurements of the initial period of rapid muscle contraction/rapid force production, as time windows are very short and errors in proper identification of contraction onset are amplified.

The potential benefit for utilizing automated methods of signal onset detection is the ability to rapidly expedite data processing and analysis by allowing for batch processing of a large number of trials. Typically, automatic methods of signal onset detection are based on an arbitrary baseline value (such as “4 N”)(Thompson et al., 2012) or reaching a percentage of the peak signal value (i.e. “2.5% of MVIC”).(Aagaard et al., 2002b, Andersen and Aagaard, 2006, de Ruiter et al., 2004b) Other potential criteria are based on the variability of the baseline signal (i.e. “onset defined as the point at which the signal deviated by more than three standard-deviations for a minimum of 25 ms above the baseline level”)(Uliam Kuriki et al., 2011) or calculating the derivative of the signal and defining onset as the zero-crossing point.(de Ruiter et al., 2007, Soda et al., 2010) Still others use more advanced algorithms with a combination/variety of criteria which must be met.(Di Fabio, 1987, Staude and Wolf, 1999)

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Conversely, there are less strict definitions as to what criteria are utilized for manual identification of signal onset. Tillin et al. define their methods as follows (Tillin et al., 2013):

> *The systematic approach to identifying contraction force onset we have used involves a trained investigator: (a) rejecting recordings where the baseline (resting) force is not stable (according to specific criteria i.e. >0.5 N in the preceding 100 ms); (b) viewing signals with a consistent scale (e.g. 500 ms vs. 1 N) that allows the envelope of the baseline noise to be clearly discerned; and (c) applying a robust definition of onset (last trough within the envelope of the baseline noise).*

Determining the point at which the signal deflects from the baseline noise is difficult if the signal has been filtered or smoothed. The use of minimal filtering and smoothing of the raw signal is encouraged to improve accuracy of signal onset detection.(Tillin et al., 2013)

To process the data obtained in this investigation, an automatic signal detection method that incorporated the beneficial aspects of both the manual and automatic detection methods was designed, which allowed for batch processing without sacrificing accuracy of onset detection. For torque signals, onset of contraction was defined as the last data point at which the torque signal either decreased or remained constant from the previous point prior to rising continuously during the initial portion of the contraction, which is equivalent to the most commonly accepted method of defining torque onset in processing RTD type contractions.(de Ruiter et al., 2007, Tillin et al., 2013) This method produced reliable and accurate results when compared to manual identification of signal onset.

### EMG Signal Onset

The variability and stochastic nature of the EMG signal makes using automated methods to accurately identify contraction onset a greater challenge. Most established automated methods

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utilize some iteration of choosing the first point outside of some measure of baseline variability (such as: "when the signal of each muscle deviated by more than three standard-deviations for a minimum of 25 ms above the baseline level [averaged over 200 ms prior the commencement of the trial]").(Uliam Kuriki et al., 2011)

A method which combines the automated evaluation of baseline variability and the definition of manual identification of signal onset (the last trough within the envelope of the baseline noise) was developed. The definition of the automated method utilized for detecting EMG signal onset in the data obtained in this investigation was:

1) The standard deviation of the first one second of data (2000 data points) from each trial is calculated for each EMG channel.
2) Beginning 400 time points (200 ms) prior to the point identified as "torque onset", the point at which the signal first exceeds eight baseline standard deviations is identified.
3) Working backward from this point, the last signal deflection prior to the increase in amplitude is selected as EMG onset.

This automated detection method was validated by comparing EMG onsets and RMS values determined from visual inspection of 20 randomly selected voluntary RTD trials (the "gold standard" method for identifying signal onset)(Tillin et al., 2010, Tillin et al., 2013) with automated processing values. The EMG onset for the three quadriceps surface EMG channels (vastus lateralis, rectus femoris, vastus medialis) for each trial were identified by visual inspection of the data. The systematic approach of Tillin et al. was used to guide this analysis.(Tillin et al., 2013) Based on these signal onsets, root mean square (RMS) amplitude of 0-50 ms and 0-200 ms was calculated for the 3 quadriceps EMG channels of each trial. These

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values were normalized to RMS EMG amplitude during ramp MVIC contractions. The peak torque of the each ramp contraction matched to the RTD contraction by leg and interval was identified, and RMS value in a 500 ms window centered at peak torque (250 ms prior to and following peak torque) was calculated. Both the time of EMG onset and the normalized RMS values were utilized for comparisons with the automated detection method.

The automated method of detecting EMG onset resulted in an average onset variation of 1-3 ms from manual identification methods. This translates to an average difference of 1-3% in 0-50 ms RMS values and 0-1% in 0-200 ms RMS values between manual and automated onset detection. The percentage differences in RMS values are amplified for shorter contractile periods, thus (as expected) the differences between manual and automated onset detection methods for 0-50ms RMS values are greater than the differences for 0-200ms RMS values. These differences would be expected to increase slightly with subsequently shorter intervals (e.g. 0-40 ms, 0-30 ms, etc.) Figure A.1 depicts three scatterplots which compare the automated method that was developed with manual identification of signal onset for each of the three quadriceps EMG channels.

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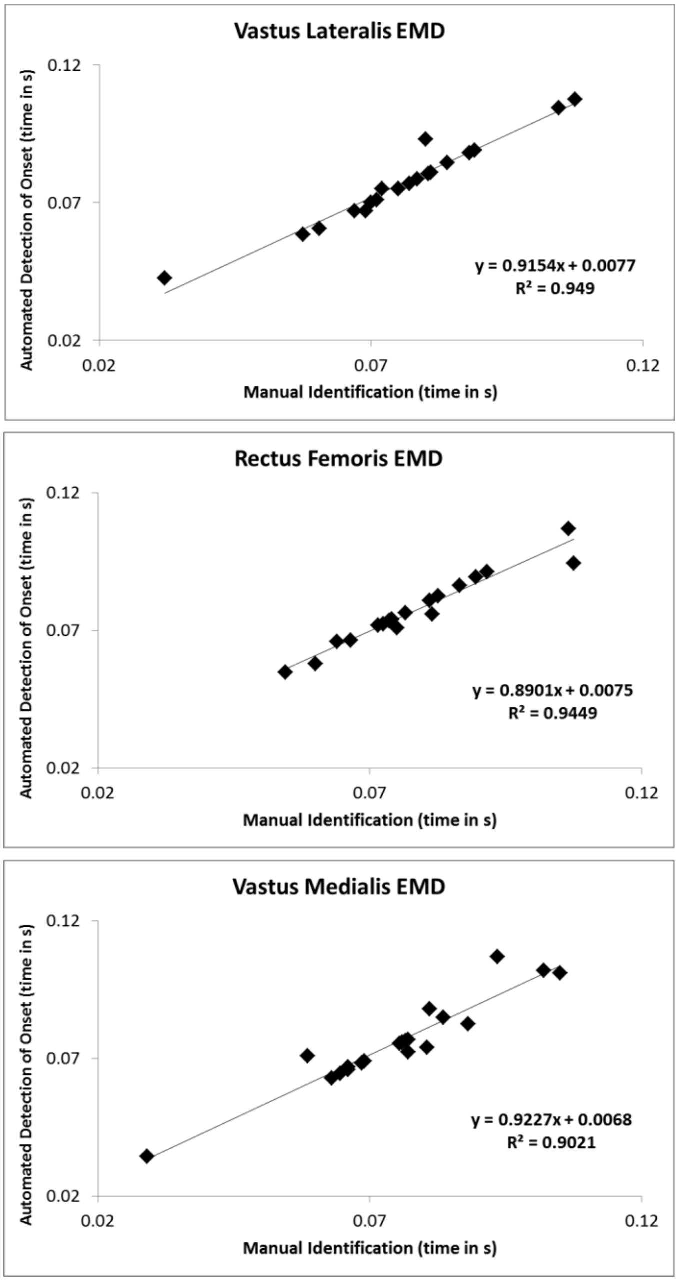

Figure A.1: Correlations between the electromechanical delay (EMD) of the quadriceps muscles calculated using manual identification of EMG onset times (X axis) and automated detection of EMG onset times (Y axis) for 20 independent trials of rapid voluntary isometric knee extension (performed by 20 different subjects). Vastus lateralis, rectus femoris, and vastus medialis EMD are depicted here.

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