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The Association Between Different Clinical Methods for Evaluating Lower Extremity Muscular Function

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ABSTRACT

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Insufficient muscular strength at the hip and thigh may increase an athlete's susceptibility to lower extremity injuries. In an attempt to reduce this risk, researchers have proposed lower limb strength testing within preparticipation physical examinations (PPE) and return-to-play (RTP) evaluations. However, because of cost, mobility, and or set-up time, some methods are not feasible in certain settings. Since methodological approaches between methods can vary, having different contraction modes and testing parameters, substitution of one method for another may not be valid. Therefore, the purpose of this study is three-fold: a) to determine the association between isometric and isokinetic contraction modes assessed at the hip, b) to investigate relationships between parameters of muscular strength, c) to assess the relationships between dynametric muscular strength and measures of functional performance.

For experiment one, eight-teen recreationally active individuals were recruited. In this experiment, separate Pearson product moment correlations were used to evaluate peak torque (PT) between modes. This experiment determined that the PT evaluated at the hip demonstrated a strong to very strong positive correlation (r =.50 - .87) between isometric and isokinetic evaluated at

60°/s, with the exception of normalized HE (r =.42) and IR (r = .24). For experiment two and three, 62 recreationally active participants were recruited. In experiment two and three, separate Pearson product-moment correlations were used to determine the association between the variables of interest. Experiment two determined that PT accounted for 78 to 98% of the variance in RTD. However, neither PT nor RTD demonstrated a similar relationship to strength endurance. Finally, experiment three, determined that work performed by participants during triple hop for distance (THD) accounted for more than 50% of the variance in absolute AB, AD, HE, HF, KE, and ER PT. In addition, the work performed during the THD also accounted for more than 50% of the variance in absolute AB and AD RTD. Overall, these three experiments indicate that in PPEs and RTP evaluations where tertiary methods might not be feasible, secondary and primary methods for evaluating muscle function may present a viable option for evaluating an individual's PT and or RTD.

This dissertation is dedicated to my wife Stephanie René. Without her love and support this accomplishment would not have been possible.

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CHAPTER I

INTRODUCTION

Insufficient muscular strength at the trunk, hip, and thigh may increase an athlete's susceptibility to certain lower extremity injuries such as noncontact ruptures of the anterior cruciate ligament (ACL) (Claiborne, Armstrong, Gandhi, & Pincivero, 2006; Kollock, Onate, & Van Lunen, 2008), patellofemoral pain syndrome (PFPS) (Niemuth, Johnson, Myers, & Thieman, 2005; Souza & Powers, 2009a, 2009b; Tyler, Nicholas, Mullaney, & McHugh, 2006), iliotibial band syndrome (ITBS) (Fredericson et al., 2000; Niemuth, et al., 2005), adductor strains (Tyler, Nicholas, Campbell, & McHugh, 2001), and hamstring strains (Croisier, Ganteaume, Binet, Genty, & Ferret, 2008). In regards to noncontact ACL tears, PFPS, and ITBS, researchers have theorized that the proximal musculature of the lower limb assists in providing stability in the frontal and transverse planes and therefore assists in the prevention of excessive hip adduction and femoral internal rotation during physical activities that involve running (Hollman, 2006; Jacobs, Uhl, Mattacola, Shapiro, & Rayens, 2007; Leetun, Ireland, Willson, Ballantyne, & Davis, 2004; Powers, 2003; Souza & Powers, 2009a, 2009b), landing from jumps (Boden, Dean, Feagin, & Garrett, 2000; Jacobs, et al., 2007), and other weight-bearing activities (Bolgla, Malone, Umberger, & Uhl, 2008; Hollman, 2006).

Several investigators have reported finding an association between proximal muscular strength and movement kinematics during weight-bearing activities (Claiborne, et al., 2006; Jacobs, et al., 2007). Claiborne, et al. (2006)

reported that concentric hip abduction strength displayed a significant moderate correlation (*r* = -0.37) with frontal plane knee motion during a single leg squat task. Lower limb proximal strength deficits also have been demonstrated to correlate with hip frontal plane motion in individuals with PFPS during bouts of prolonged walking according Dierks, et al. (2008). They reported significant strong negative correlations (r = -0.74) between hip abduction strength and hip adduction angles with prolonged running in participants with patellofemoral pain syndrome, but not for the uninjured control group. This observed weakness in symptomatic patients engaged in prolonged running corresponds with findings by Fredericson, et al. (2000) who reported that men and women long distance runners suffering from ITBS displayed significantly less normalized hip abductor torque (strength) than controls. Although no kinematic data were collected, the researchers postulated that ITBS might be a consequence of increased tension to the ITB due to the inability of the hip abductors to minimize excessive hip adduction and internal rotation (resulting in an increased knee valgus vector). This increased tension results in the ITB impingement upon the lateral epicondyle of the femur during prolonged running (Fredericson, et al., 2000). It should however be noted that it is currently unclear if the observed weakness was the cause or result of each of these particular pathologies These reports together with other similar findings (Jacobs, et al., 2007; Souza & Powers, 2009b) suggest that this proposed premise is not without evidence. Therefore leading some investigators to suggest that coupled with other biomechanical factors, proximal lower extremity weakness may lend to aberrant lower limb movement mechanics and subsequently increasing the likelihood of injury during weight bearing activities (Hollman, 2006; Souza & Powers, 2009b).

Muscular strength deficits have not only been implicated in aberrant movement mechanics during weight-bearing activities, but also have been linked to lower extremity muscle strains particularly for the hip adductors and hamstrings (Orchard, Best, & Verrall, 2005). Tyler, et al. (2001) reported that athletes in the National Hockey League who sustained adductor strains during the season displayed 18% less preseason hip adductor strength as compared to uninjured athletes. They also reported that preseason adduction strength was 95% of abduction strength in the uninjured athlete, while only 78% of abduction strength in injured athletes. Similar findings have been reported concerning the hamstring musculature. Orchard, et al.(1997) reported that hamstring muscle weakness was associated with an increased risk of hamstring muscle strains in Australian Rules football players. The group reported that preseason hamstring strength was 16% lower in injured versus uninjured athletes. In a more recent study, Croisier, et al. (2008) reported that 16.5% of players with pre-season hamstring-quadriceps imbalances that remained untreated throughout the season suffered hamstring strains; resulting in a relative risk (RR) index of 4.66. The investigators concluded that soccer activity with untreated hamstring-quadriceps strength imbalances increases the risk of hamstring injuries more than 4-fold in comparison with players with normal strength profiles.

Findings such as these have caused researchers and health-care professionals to re-evaluate the conventional models of determining an athlete's physical readiness prior to sports participation. In response to the potential risk presented by muscular imbalances and bilateral strength deficits, investigators (Augustsson, Thomee, & Karlsson, 2004; Gustavsson et al., 2006; Ostenberg, Roos, Ekdahl, & Roos, 1998; Scott, Bond, Sisto, & Nadler, 2004) have proposed inclusion of computer-based strength assessments (Croisier, et al., 2008; Scott, et al., 2004) and or “low- tech” measures of functional performance (e.g. single leg hopping tasks) (Augustsson, et al., 2004; Gustavsson, et al., 2006; Ostenberg, et al., 1998) into traditional pre-participation physical examinations (PPE) (Ostenberg, et al., 1998; Scott, et al., 2004) or return-to-play (RTP) (Augustsson, et al., 2004; Gustavsson, et al., 2006) criterion as a means of identifying lower extremity strength deficits. These types of high and low-tech methods can be classified into tertiary (e.g., isokinetic dynamometry), secondary (e.g., portable –fixed dynamometry), and primary (e.g. single leg hopping tasks) methods of evaluating muscular strength (Kollock, et al., 2008; Kollock, Onate, & Van Lunen, 2010). Factors such as cost, portability, accessibility, and time often determine the method employed (Kollock, et al., 2008, 2010).

Presently, tertiary class computer-based evaluations (i.e. isokinetic strength evaluations) are coupled with measures of functional performance (e.g., single leg hopping tasks) as part of standard ACL reconstruction (RECON) return-to-play criteria (Brotzman, 1996; Prentice, 1999; Prentice & Voight, 2001; Wilk, Arrigo, Andrews, & Clancy, 1999). However, due to issues of feasibility, the use of isokinetic evaluations are unconventional in RTPs following an injury not requiring surgical intervention (e.g. PFPS and ITBS) and in PPEs undertaken in youth and high school settings (Hamilton, Shultz, Schmitz, & Perrin, 2008). Although, isokinetic dynamometry is considered the gold standard of strength assessments (Martin et al., 2006), the lack of utilization is perhaps due to the cost of equipment (Bohannon, 1990; Scott, et al., 2004) (approximately $50,000-$60,000) and lack of portability (Bohannon, 1990; Hill, 1996; Martin, et al., 2006) limits the accessibility and use as a tool for helping to determine an athlete's RTP status to larger outpatient clinics or hospital physical rehabilitation facilities. Additionally, due to tedious set-up protocols this type of instrumentation would not be conducive for testing large numbers of athletes in succession during large-scale PPEs at the high school or university settings (Hill, 1996; Scott, et al., 2004). Many consider the use of portable computer-based isometric assessments and or measures of functional performance ideal in the PPE and RTP scenarios due to their validity, reliability, and ease of test administration (Augustsson, et al., 2004; Gustavsson, et al., 2006; Ostenberg, et al., 1998; Scott, et al., 2004). In terms of the relationship of isometric to isokinetic evaluations researchers have reported strong correlations when evaluating knee flexor and extensor maximum strength protocols (Hill, 1996; Jameson, Knight, Ingersoll, & Edwards, 1997; J. J. Knapik, J. E. Wright, R. H. Mawdsley, & J. M. Braun, 1983b), however this same relationship may not hold true for hip strength protocols.

Currently, there are no studies in the literature investigating the association between isometric and isokinetic hip strength protocols. Thus, the question remains if portable isometric computer-based instrumentation is a valid substitute for isokinetic test batteries at the hip. In addition, most literature using dynametric strength evaluations within the context of assessing athletic readiness or strength as an injury risk factor have focused on maximum strength assessments with minimal attention given to other aspects of muscular strength (Askling, Saartok, & Thorstensson, 2006; Croisier, et al., 2008; Keays, Bullock-Saxton, Newcombe, & Keays, 2003; McHugh, Tyler, Tetro, Mullaney, & Nicholas, 2006; Ostenberg, et al., 1998; Tyler, et al., 2001). This is problematic considering many believe muscular strength is comprised of separate aspects or parameters (i.e. maximum strength, rate of force development, and strength endurance). In sports and other strenuous activities, the ability to produce adequate levels of strength rapidly and or to sustain it may be equally important to performance and the susceptibility of injury or re-injury. To date there have been no studies investigating the relationship between all three parameters (i.e. maximum strength, rate of force development, and strength endurance) of muscular strength under single joint isometric conditions. The lack of research into the relationship between these aspects raises the question of the potential necessity of evaluating all three parameters.

This relationship has been assessed in part, in that several studies have assessed the association of maximum strength to both rate of force development and strength endurance. Andersen and Aagaard (2006) reported that maximum strength assessed at the knee extensors accounted for approximately 80% of the total variance in rate of force development during the later phase (150-250 milliseconds [ms]) of the muscle contraction. They also reported observing that as the rate of force development time interval decreased so did the association with maximum strength, with these same findings being reported in the upper extremities between maximum strength and the maximum rate of force production by Mirkov, et al. (2004). In regards to the relationship between maximum strength and strength endurance Surraka et al. (2004) reported finding a significant moderate correlation (*r*= 0.48) between the two variables when assessed at the knee flexors of patients with multiple sclerosis (MS), however the group did not find this same relationship for the knee extensors. The lack of association between maximum strength and strength endurance has also been reported in the upper extremities. Meldrum, et al. (2007) reported observing that there was no correlation between hang grip maximum voluntary muscular strength and strength endurance. Schwid, et al. (1999) and Sanjak et al. (2001) also reported similar findings, indicating the importance of measuring both aspects (Meldrum, et al., 2007). Currently, to the author's knowledge the relationship between rate of force development and strength endurance has been investigated in neither the upper nor the lower extremities.

Although, portable computer-based isometric assessments are valid, reliable, and feasible for use in both PPE and RTP evaluations, does the use of advanced isometric evaluations provide information unobtainable through less sophisticated and more cost effective methods (e.g. measures of functional performance such as single leg hopping tasks) of assessing muscular function. Functional performance test batteries are frequently used by health-care providers to assess general lower limb function in a dynamic capacity (Docherty, Arnold, Gansneder, Hurwitz, & Gieck, 2005). Functional performance test batteries can encompass numerous components critical to injury free sports participation such as strength (Hamilton, et al., 2008; Keays, et al., 2003), power (Hamilton, et al., 2008; Keays, et al., 2003), and agility (Keays, et al., 2003) across multiple joints of the lower limb. Functional performance testing is often recommended as one component of a battery of assessments to establish an athlete's readiness to return-to-play (Gustavsson, et al., 2006; Hopper, Strauss, Boyle, & Bell, 2008; Keays, et al., 2003). Gustavsson, et al. (2006) reported finding that functional performance test batteries consisting of the single-limb vertical jump, hop for distance, and side hop test displayed a high ability to discriminate between the performance of the injured and uninjured side in patients six months post ACL reconstruction. Functional performance tests have also been observed to predict isokinetic maximum knee flexor and extensor strength at 60 and 180°/s (Hamilton et al, 2008). Hamilton, et al. (2008) reported that the triple hop test for distance was a strong predictor of isokinetic hamstring and quadriceps strength at 60 and 180°/s with the triple hop for distance explaining 49-58.8% of the variance. However, these same findings have not been reported for other proximal muscle groups such as the hip abductors and adductors. Furthermore, the literature comparing isometric strength to measures of functional performance limited.

Summary

Muscular strength deficits at the trunk, hip, and thigh may increase an athlete's susceptibility to certain lower extremity sprains, strains and overuse injuries (Claiborne, et al., 2006; Souza & Powers, 2009b; Tyler, et al., 2001). In an attempt to minimize this potential link, researchers have proposed the use of computer-based isometric strength testing prior to athletic participation (Kollock, et al., 2010; Scott, et al., 2004). Computer-based isometric assessments have shown strong correlations isokinetic testing when evaluated at the knee flexor and extensor maximum strength, but this same relationship may not hold true for the musculature at the hip (Hill, 1996; Jameson, et al., 1997; Knapik, et al., 1983b) . In addition, there appears to be limited research into other aspects of muscular strength (Askling, et al., 2006; Croisier, et al., 2008; Keays, et al., 2003; McHugh, et al., 2006; Ostenberg, et al., 1998; Tyler, et al., 2001) such as rate of force development and strength endurance (Castro-Piñero et al., 2010; Mebes et al., 2008). Although, portable computer-based isometric assessments possess the system flexibility to assess all aspects or parameters of muscular strength there use may not provide information unobtainable through more cost effective methods (e.g. measures of functional performance such as single leg hopping tasks). Therefore, the main question to be answered through this dissertation is can we substitute techniques and instruments that are more cost effective and time efficient for more sophisticated types of instrumentation.

Experiment I: Assessing Hip Strength: A Comparison of Isometric Portable Fixed Dynamometry to Isokinetic Dynamometry at 1.05 rad·s^{-1} [60°·s^{-1}]

Purpose Statement

The purpose of this experiment will be to determine the association between static and isokinetic contraction modes. The specific aim of experiment one will be to determine the relationship between hip isometric and isokinetic maximum strength performed at 1.05 rad·s^{-1} [60°·s^{-1}].

Null Hypothesis

There will be no correlation between hip isometric and concentric isokinetic maximum strength (i.e. absolute peak and normalized peak torques) at 1.05 rad·s^{-1} [60°·s^{-1}]

Alternative Hypothesis

There will be a significant moderate to strong positive correlation between hip isometric and concentric isokinetic maximum strength (i.e. absolute peak and normalized peak torques) at 1.05 rad·s^{-1} [60°·s^{-1}]

Variables of Interest

The following measures of strength will be assessed: hip flexion, hip extension, hip abduction, hip adduction, hip internal rotation, and hip external rotation. Maximum Strength will be defined as the maximum absolute and normalized peak torque value, see following equations:

- Torque [Nm] = moment arm [m] x force [N]
- Normalized Torque = (Torque [Nm] / (weight [N] x height [m]) x 100 (Bolgla, et al., 2008; Fredericson, et al., 2000; Krause, Schlagel, Stember, Zoetewey, & Hollman, 2007)

Experiment II: Maximum Strength and its use as an Indicator of Rapid Force Production and Endurance Strength

Purpose Statement

The purpose of this experiment will be to investigate relationships between three parameters of muscular strength. The specific aim of experiment two will be to determine the relationships between the isometric strength parameters of maximum strength, rate of torque development (RTD), and strength endurance assessed at the hip and knee.

Null Hypothesis

There will no correlations between maximum strength, strength endurance (calculated via fatigue index (FI) equation), and RTD at four separate time intervals (0-30, 0-50, 0-100, and 0-200 ms) for measurements taken at the hip and knee.

Alternative Hypothesis One

There will be a positive moderate to strong correlation between maximum strength and RTD at four separate time intervals (0-30, 0-50, 0-100, and 0-200 ms) (Mirkov, et al., 2004) for measurements taken at the hip and knee.

Alternative Hypothesis Two

The isometric parameters of maximum strength and RTD at four separate time intervals (0-30, 0-50, 0-100, and 0-200 ms) will have a significant positive moderate to strong correlation with the isometric strength parameter of strength endurance (i.e. FI ratio) (Meldrum, et al., 2007; Schwid, et al., 1999) for measurements taken at the hip and knee.

Variables of Interest

The following measures of strength will be assessed at the hip flexors, hip extensors, hip abductors, hip adductors, hip internal rotators, hip external rotators, knee flexors, and knee extensors:

Maximum Strength. Maximum strength will be defined as the maximum raw [absolute] and normalized peak torque value (%T), see following equations:

- Torque [Nm] = moment arm [m] x force [N]
- Normalized Torque = (Torque [Nm] / (weight [N] x height [m]) x 100 (Bolgla, et al., 2008; Fredericson, et al., 2000; Krause, et al., 2007)

Rate of Torque Development ($Nm{\cdot}s^{-1}$). Rate of torque development [Nm/s] at four separate time intervals: 0 – 30, 0 – 50, 0 – 100, and 0 - 200 (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002; Anderson, Madigan, & Nussbaum, 2007; Christensen et al., 2008)

- RTD [$Nm{\cdot}s^{-1}$] = Δtorque [Nm]/Δtime [s]
- Normalized RTD = (RTD [$Nm{\cdot}s^{-1}$]/(weight [N] x height [m])) x 100

Strength Endurance. Strength endurance will be defined through the calculation of a fatigue index ratio score (FI), see equation below:

- FI = (1 – (area under the torque-time curve [AUTC] / hypothetical area under the torque-time curve [HAUTC])) x 100 (Meldrum, et al., 2007; Sanjak, et al., 2001; Schwid, et al., 1999; Surakka, Romberg, Ruutiainen, Virtanen, et al., 2004)

Experiment III: The Relationship of Isometric Strength to Measures of Functional Performance

Purpose Statement

The purpose of this experiment will be to assess the relationships between dynametric muscular strength and measures of functional performance. The specific aim of this experiment is to determine the relationships of isometric strength (i.e. maximum strength, RTD, and strength endurance) assessed at the hip and knee to measures of physical performance.

Null Hypothesis

The isometric strength parameters of maximum strength, strength endurance (calculated via a fatigue index (FI) equation), and RTD at four separate time intervals (0-30, 0-50, 0-100, and 0-200 ms) will not be correlated to the following measures of physical performance.

- Single leg vertical jump measured in centimeters [cm]
- Single hop for distance measured in cm
- Triple hop test for distance measured in cm
- Crossover hop test for distance measured in cm
- *30 sec*ond lateral hop test for endurance measured in cm

Alternative Hypothesis One

The isometric strength parameters of maximum strength and RTD at four separate time intervals (0-30, 0-50, 0-100, and 0-200 ms) will have a positive moderate to strong correlation with the following measures of functional performance (Hamilton, et al., 2008; Jameson, et al., 1997; Keays, et al., 2003; Ostenberg, et al., 1998)

- Single leg vertical jump measured in cm
- Single hop for distance measured in cm
- Triple hop test for distance measured in cm
- Crossover hop test for distance measured in cm

Alternative Hypothesis Two

The isometric strength parameters of maximum strength(Ostenberg, et al., 1998) and RTD at four separate time intervals (0-30, 0-50, 0-100, and 0-200 ms) will have a negative moderate to strong correlation with the following measure of functional performance.

- 30 second (s) lateral hop test for endurance

Alternative Hypothesis Three

There will be a significant positive moderate to strong correlation between strength endurance (i.e. FI ratio) and the following measures of functional performance

- Single leg vertical jump measured in cm
- Single hop for distance measured in cm
- Triple hop test for distance measured in cm
- Crossover hop test for distance measured in cm

Alternative Hypothesis Four

There will be a significant negative moderate to strong correlation between the strength endurance fatigue index ratio and the following measure of functional performance.

- 30 s lateral hop test for endurance

Variables of Interest

The following measures of strength will be assessed at the hip flexors, hip extensors, hip abductors, hip adductors, hip internal rotators, hip external rotators, knee flexors, and knee extensors:

Maximum Strength. Maximum strength will be defined as the maximum raw [absolute] and normalized peak torque value (%T), see following equations:

- Torque [Nm] = moment arm [m] x force [N]
- Normalized Torque = (Torque [Nm] / (weight [N] x height [m]) x 100 (Bolgla, et al., 2008; Fredericson, et al., 2000; Krause, et al., 2007)

Rate of Torque Development ($Nm{\cdot}s^{-1}$). Rate of torque development [Nm/s] at four separate time intervals: 0 – 30, 0 – 50, 0 – 100, and 0 - 200 (Aagaard, et al., 2002; Anderson, et al., 2007; Christensen, et al., 2008)

- RTD [$Nm{\cdot}s^{-1}$] = Δtorque [Nm]/Δtime [s]
- Normalized RTD = (RTD [$Nm{\cdot}s^{-1}$]/(weight [N] x height [m])) x 100

Strength Endurance. Strength endurance will be defined through the calculation of a fatigue index ratio score (FI), see equation below:

- FI = (1 – (area under the torque-time curve [AUTC] / hypothetical area under the torque-time curve [HAUTC])) x 100 (Meldrum, et al., 2007; Sanjak, et al., 2001; Schwid, et al., 1999; Surakka, Romberg, Ruutiainen, Virtanen, et al., 2004)

The following measures of functional performance for the dominant limb: single leg hop for distance, triple hop for distance, crossover hop for distance, and 30 s lateral hop test for endurance.

Single Leg Vertical Jump. The single leg vertical jump will consist of two separate variables:

- Height jumped in centimeters
- Work [joules] = mass [kg] x gravity x distance [m])

Single Hop for Distance. The single hop test for distance will consist of two separate variables:

- Distanced hopped in centimeters
- Work [joules] = mass [kg] x gravity x distance [m])

Triple Hop for Distance. The triple hop test for distance will consist of two separate variables:

- Distanced hopped in centimeters
- Work [joules] = mass [kg] x gravity x distance [m])

Crossover Hop Test for Distance. The variable for the crossover hop test will be the following:

- Distance hopped in centimeters

30 s Lateral Hop Test for Endurance. The variable of interest for the 30 s lateral hop test for distance will be the following:

- number of hops performed over a 30 s period

Operational Definitions

- Isometric Contraction – A force produced by the muscle group against an immovable resistance at a specific joint angle (no shortening or lengthening) (Enoka, 2002; Oatis, 2004).

- Concentric Contraction – A muscle contraction in which the muscle torque is greater than the load torque and as a consequence the active muscle shortens (Hamill & Knutzen, 2003; Oatis, 2004).
- Eccentric Contraction – A muscle contraction in which the load torque is greater than the muscle torque and as a consequence the active muscle is lengthened (Hamill & Knutzen, 2003; Oatis, 2004).
- Isokinetic dynamometry – Provides an accommodating resistance at a constant velocity throughout the full range of motion (Brown, 2000; Deighan, 2003; Hill, 1996; Purkayastha, Cramer, Trowbridge, Fincher, & Marek, 2006; Schmitz & Westwood, 2001).
- Isotonic dynamometry – Allows full range of motion, however, the velocity is not constant, and is dependent on the subject to overcome inertia to move the

load (Enoka, 2002; Kovaleski, Heitman, Trundle, & Gilley, 1995; Purkayastha, Cramer, Trowbridge, Fincher, & Marek, 2006).

- Maximum Strength (Smax) – Also termed peak force or torque. The force or tension a muscle group can exert against a resistance in one maximal effort under dynamic concentric, dynamic eccentric or isometric conditions (Hislop & Perrine, 1967; Oatis, 2004).
- Peak Torque (PT) – The highest level of voluntary force produced by a muscle around an axis under isometric, eccentric, and concentric conditions (Mebes, et al., 2008).
- Rate of Force Development (RFD) – Is the ability of a muscle group to generate force quickly. It more clearly is the rapid production of force by a muscle group over three seconds and can be expressed as (ΔForce/ΔTime) (Aagaard, et al., 2002; Andersen & Aagaard, 2006).
- Strength Endurance (SE) – Is the muscle or muscle groups ability to resist fatigue under anaerobic strength conditions and is based on anaerobic capacity (Mebes, et al., 2008).
- Total Contractile Impulse (TCI) – Represented as the area under the force-time curve and is numerically expressed as the product of the average force and time in seconds. It is identical to the kinetic impulse or momentum of the lower limb if it had been allowed to move (Aagaard, et al., 2002; Enoka, 2002).
- Recreational Athlete – an individual engaged in at least 30 minutes of physical activity (e.g. biking, soccer, basketball, volleyball, running,

swimming, tennis, or weight training) 2-3 times per week and is not currently involved in an in-season intercollegiate or professional sport.

- Physically Active – Individuals engaged in either 150 minutes of "moderate" intensity physical activity a week or 75 minutes of minutes of "vigorous" intensity physical activity a week (American College of Sports Medicine., Thompson, Gordon, & Pescatello, 2010; Ronai, 2009; US Department of Health and Human Services, 2008).

- Single Leg Hop for Distance (SLHD) – A single-limb hopping task in which the performer of the task stands on one limb and with a maximal effort hops as far as possible landing on the same limb as take-off (Ostenberg, et al., 1998; Tegner, Lysholm, Lysholm, & Gillquist, 1986).

- Triple Hop for Distance (THD) – A single-limb hopping task in which the performer of the task stands on one limb and hops using a maximal effort as far as possible three consecutive times on the same limb (Reid, Birmingham, Stratford, Alcock, & Giffin, 2007; Ross, Langford, & Whelan, 2002).

- Crossover Hop for Distance (CHD) – A single-limb hopping task in which the performer stands on one limb and hops forward exerting a maximal effort as far as possible three consecutive times while alternately crossing over marking (Reid, et al., 2007; Ross, Langford, et al., 2002).

- 30 second Lateral Hop test for Endurance – A single-limb hopping task in which the performer of the task stands on one limb and hops in a side-to-side manner (laterally and medially) landing in between two parallel line 40 centimeters apart for a 30 second period (Gustavsson, et al., 2006; Itoh, Kurosaka, Yoshiya, Ichihashi, & Mizuno, 1998).

- Single Leg Vertical Jump – A single-limb jumping tasks in which the performer of the task stands on one limb and jumps a single time in a vertical direction using maximum effort and lands on the same limb.

Assumptions

The assumptions of this study are as follows:

- Subjects will truthfully report their injury history, level of participation in sports, and other parameters necessary for inclusion into the study.
- All subjects will give a maximum effort on all strength and measures of functional performance
- All subjects will follow the directions and will refrain from a rigorous lower extremity workout or weight lifting at least 12 hours prior to their testing session.
- All equipment utilized within the study will be calibrated and or undergo a measurement verification process prior to testing.

Limitations

The researcher(s) have established the following limitations:

- The subjects' lifestyles and other activities may have an effect on the results of this study
- The effects of fatigue may skew the findings of the study

- The findings of the individual experiments may be limited to the sample, which is one of convenience
- The varied athletic participation and years of experience of each participant within their perspective sport or activity may influence their performance on the computer-based strength and functional performance tasks subsequently effecting the results of the study
- All measures of functional performance will be evaluated in a laboratory setting
- All participants in this study will be healthy asymptomatic individuals, thus participants with lower limb injuries such as acute ligament sprains, PFPS, ITBS, or muscle strains may not presents similar findings.

Delimitations

The researcher(s) have established the following delimitations:

- All subjects were healthy and able to understand all testing directions
- The ages of the subjects will range from 18-36
- All subjects recruited will be recreational athletes as defined by the American College of Sports Medicine (ACSM)
- Subjects will all be from the same geographical area (Hampton Roads Community, VA).
- All strength and measures of functional performance were performed on the dominant limb

- *Subjects do not have a history of significant hip or knee surgery, traumatic* patellar dislocation or neurological involvement that would have an effect on gait.

CHAPTER II

LITERATURE REVIEW

Lower extremities injuries such as noncontact ACL tears, PFPS, ITBS, and muscle strains (e.g., hamstring) of the upper leg or thigh region are common within athletic and sports settings. Non-contact anterior cruciate ligament (ACL) tears are a debilitating knee injury and account for 70% -80 % of all ACL injuries (Boden, et al., 2000). Noncontact ACL tears are common in sports requiring rapid deceleration and an abrupt change of direction (Olsen, Myklebust, Engebretsen, & Bahr, 2004). In the United States, about 250,000 ACL injuries occur annually of which 100,000 require surgical repair (Griffin et al., 2006; Myer, Ford, & Hewett, 2004). Healthy, active persons engaged in competitive sports, such as basketball, volleyball, and soccer, account for 70% of all incidences (Feagin et al., 1987). The average cost of diagnosis, surgical repair, and rehabilitation for an ACL tear ranges from $17,000 to $25,000 per incident with a total annual cost of this lower extremity injury ranges from 6.4 million – 1 billion dollars (Griffin, et al., 2006; Hewett, Lindenfeld, Riccobene, & Noyes, 1999; Myer, et al., 2004). PFPS and ITBS result from repetitive activities such as running. It has been reported that an estimated forty million people in the United States participate in running activities, of those 27%- 70% sustain some type of knee injury (Hreljac, Marshall, & Hume, 2000; Jacobs & Berson, 1986; Macera et al., 1989; Marti, Abelin, & Minder, 1988; McCrory et al., 1999; Wen, Puffer, & Schmalzried, 1998). Reports reveal that approximately 25% of those injuries are PFPS (Baquie & Brukner, 1997; Devereaux & Lachmann, 1984; Stefanick, 2004; Taunton et al., 2002). More currently in a sample of 2002 runners 42.1% of all injuries were knee related with PFPS and ITBS accounted for 331 and 168 patient cases respectively (Taunton, et al., 2002). Finally, hamstring strains are common in sports that involve high-intensity sprinting effort such as Australian Rules Football (Orchard & Seward, 2002). In the Australian Football League, hamstring strains have been one of the most common injuries representing 12-15% of all injuries (Orchard & Seward, 2002; Woods et al., 2004), with a incidence of 4.5 per team per season (Orchard & Seward, 2002). In this particular population this injury carries a reoccurring rate of 34% (Orchard & Seward, 2002).

In response to these reports, researchers have begun trying to identify the mechanisms and factors associated with these injuries (Croisier, et al., 2008; Engebretsen, Myklebust, Holme, Engebretsen, & Bahr, 2010; Powers, 2003; Souza & Powers, 2009b; Woods, et al., 2004). One potential risk factor reported within the literature is insufficient lower extremity muscular strength at the trunk, hip, and thigh (Fredericson, et al., 2000; Souza & Powers, 2009b; Tyler, et al., 2001). This finding has led many to advocate the use of muscular strength assessments in order to better identify athletes with bilateral and agonist-antagonist strength deficits during preparticipation physical examinations (PPE) (Nadler, Malanga, DePrince, Stitik, & Feinberg, 2000; Scott, et al., 2004; Tyler, et al., 2001) or while assessing an athlete's status prior to return-to-play (RTP) (Augustsson, et al., 2004; Best & Brolinson, 2005; Hopper, et al., 2008; Neeter et al., 2006).

Within the literature, researchers have chosen to evaluate muscular function through numerous methods (Augustsson, et al., 2004; Claiborne, et al., 2006; Neeter, et al., 2006; Souza & Powers, 2009a, 2009b). Some have selected the use of single joint isometric (Cichanowski, Schmitt, Johnson, & Niemuth, 2007; Fredericson, et al., 2000; Niemuth, et al., 2005), isotonic (Cheng & Rice, 2005; J. J. Knapik, J. E. Wright, R. H. Mawdsley, & J. Braun, 1983a; Kovaleski, Heitman, Trundle, & Gilley, 1995; Stauber, Barill, Stauber, & Miller, 2000), and isokinetic (Cometti, Maffiuletti, Pousson, Chatard, & Maffulli, 2001; Deighan, 2003; Hill, 1996; Hsu, Tang, & Jan, 2002) evaluations, while others have sought to evaluate the ability of the lower limb using a more functional approach (i.e. functional performance testing) (Augustsson, et al., 2004; Neeter, et al., 2006).

These different methodological approaches can be classified into tertiary, secondary, and primary methods for evaluating muscular strength (Kollock, et al., 2008, 2010). The tertiary category of assessments represents the highest class of strength testing (Kollock, et al., 2008, 2010), which include isokinetic devices such as the Primus RS (BTE Technologies, Hanover, MD) and Biodex System 4 (Biodex Corp, Shirley, NY) (Kollock, et al., 2008). Although arguably these instruments are considered by many as the gold standard of strength assessments (Martin, et al., 2006), they present several logistical limitations. Isokinetic instrumentation is often quite costly, lacks portability, and is not very practical when testing large numbers of athletes in succession during large scale screening examinations (Kollock, et al., 2008, 2010). Secondary methods of assessing strength include such devices as hand-held and portable-fixed dynameters (Kollock, et al., 2008, 2010). Instruments in this category are portable, provide objective measures, and require minimal set-up time (Kollock, et al., 2008, 2010). The most basic class is primary methods of evaluating muscular strength (Kollock, et al., 2008, 2010). These techniques and instruments are often performed at a nominal cost, because they require minimal equipment, administration time and instruction (Kollock, et al., 2008, 2010). A primary strength assessment method (e.g., measures of functional performance such as single leg hopping tasks) is often low-tech and is ideal for use at athletic practice sites or competitive events and in a clinical setting where secondary or tertiary assessment might not be feasible (Kollock, et al., 2010).

Researchers have proven methods from each class to be reliable methods for the evaluation of muscle function (Agre et al., 1987; Bohannon, 1997a; Clark, Condliffe, & Patten, 2006; Deighan, 2003; Ross, Langford, et al., 2002; Symons, Vandervoort, Rice, Overend, & Marsh, 2005; Webber & Porter, 2010). In particularly, strong associations have been reported between certain measures functional performance and isokinetic maximum knee strength (Bjorklund, Skold, Andersson, & Dalen, 2006; Hamilton, et al., 2008; Ostenberg, et al., 1998; Tsiokanos, Kellis, Jamurtas, & Kellis, 2002) with similar findings reported for the relationship between isometric and isokinetic maximum knee strength (Hill, 1996; Jameson, et al., 1997; Knapik, et al., 1983b). However, several gaps exist within the literature. First to the author's knowledge there is no empirical information into whether or not these same relationships persist between isometric and isokinetic maximum strength at the musculature at the hip. Second, to date there is limited information comparing either rate of force development or strength endurance to maximum strength or functional performance. A clearer understanding of these relationships is warranted. This understanding is critical to helping the health-care provider make evidence based decisions pertaining to the aspects of strength (maximum strength, rapid force production, or strength endurance) tested and methods (e.g., computer-based or "low tech" functional performance testing) used for evaluating muscle function during PPEs and RTPs. Furthermore, since clinicians (especially athletic trainers at high school settings) often have minimal time and or financial resources (Wham, Saunders, & Mensch, 2010), additional elements included into already existing PPEs and RTPs need to be essential and measured in the most cost effective manner.

Preparticipation Physical Examinations

The practice of PPEs is quite common in the United States with most high schools, universities, athletic associations, and professional groups requiring that athletes undergo some type of medical examination before sports participation due to legal and insurance requirements (Wingfield, Matheson, & Meeuwisse, 2004). The main purpose of PPEs from both a legal and medical standpoint is to screen an athlete for injuries or medical conditions that might interfere with or worsen with athletic participation (Wingfield, et al., 2004). PPEs generally require a comprehensive health history, relevant physical examination emphasizing cardiovascular, neurological, and musculoskeletal evaluations (American College of Sports Medicine., 2005; National Collegiate Athletic Association., 2010-2011)

Many also recommend inclusion of high-risk behaviors (e.g. substance abuse), issue unique to female athletes (e.g. disordered eating), and menstrual history to be added to current health history sections of PPEs (American Academy of Family Physicians., 2010; Joy, Paisley, Price, Rassner, & Thiese, 2004). From a lower extremity injury prevention standpoint, however, most current PPEs screening procedures are inadequate (Wingfield, et al., 2004) for accurate identification of injury risk (Bradford & Lyons, 1991). Procedures for computer-based assessments of muscle strength at the trunk, hip, and thigh are not typically included. This is perhaps due to the cost and accessibility of the equipment (Bohannon, 1990; Hamilton, et al., 2008). Early identification of proximal lower extremity muscular weakness and imbalance, through the integration of portable computer-based strength testing into the PPE, may provide evidence of a need for implementation of a specific strengthening program that will reduce the incidence of lower extremity injury. Conventional PPEs also fail to assess an athlete's ability to perform functional activities (e.g. single leg hopping tasks) specific to the sport. Functional performance testing allows healthcare practitioners to evaluate the ability of an athlete to perform exercise maneuvers that simulate sport specific actions (Creighton, Shrier, Shultz, Meeuwisse, & Matheson, 2010). A functional performance test battery within a PPE to mimic the forces and stresses experienced in a competitive situation (Clark, 2001), would allow clinicians to evaluate the athlete's integration of muscular strength, range of motion, proprioception, and endurance (Creighton, et al., 2010). Functional performance testing also may provides a low-cost and time-efficient method for assessing muscle function and functional joint stability during administration of a PPE since they require minimal equipment and time (Hamilton, et al., 2008) . Although clinicians do not traditionally use portable computer-based strength and functional performance testing methods during the PPE screening process, their use is perhaps ideal in the PPE scenarios due to their validity, reliability, and ease of test administration, which allows clinicians to assess large numbers of athletes in succession during large-scale PPEs.

Return-to-Play Criterion

The decision to return an athlete to play following musculoskeletal injury is ideally the result of a thoughtful and highly informed process of evaluation, treatment, and rehabilitation. Prior to RTP, in reaching a decision to return an athlete to full competition, clinicians must attempt to answer questions such as the following. What is the actual status of healing? How do we determine it? Is the athlete able to perform sport-specific skills at an appropriate level? Does returning the athlete at this point place him/her at risk for injury or reinjury?

For much of the nonsurgical musculoskeletal injuries such as PFPS and ITBS there is a lack of standardized RTP guidelines. This absence of standard RTP guidelines can be the source of confusion and disagreement for clinicians (Clover & Wall, 2010; Creighton, et al., 2010). To help assist with answering some of these questions and in making informative decisions regarding an athlete's RTP status following a musculoskeletal injury, clinicians could employ the use computer-based strength evaluations and or a battery of functional performance tests. Best and Brolinson (2005) proposed decision based RTP model that included functional performance test batteries. Presently, both computer-based strength evaluations and functional performance test batteries are included in standard ACL RECON RTPs. Prior to release to unrestricted sports participation following 4-6 month accelerated ACL RECON rehabilitation protocol emphasizing immediate range of motion and weight bearing (Kvist, 2004), athletes must meet a set criteria for release (i.e. return to play criteria). Although, the specific return-to- play criteria varies across hospitals, clinics, and physicians the basic elements normally include isokinetic strength and functional performance test batteries (Brotzman, 1996; Brotzman & Wilk, 2003; Prentice, 1999; Prentice & Voight, 2001; Wilk, et al., 1999).

However, in many high settings in which access to computer-based is limited perhaps due to financial resources (Wham, et al., 2010) the use of both methods may not be feasible. Functional performance test batteries (incorporating single and triple hop tests for distance), while normally not providing precise data on individual muscle groups, have shown strong to very strong correlations (r = 0.50 to 0.89) with quadriceps and hamstring isokinetic evaluations at certain velocities (e.g. 60 and 180°/s) (Bjorklund, et al., 2006; Hamilton, et al., 2008; Ostenberg, et al., 1998; Tsiokanos, et al., 2002) . To date most of the investigations into the association muscular strength to functional performance or isometric to isokinetic mode contraction have mainly focused on maximum strength (i.e. peak torque) (Bjorklund, et al., 2006; Hamilton, et al., 2008; Ostenberg, et al., 1998; Tsiokanos, et al., 2002). The peak torque measures alone may not be representative of other aspects of muscle function such as rate of torque development and strength endurance. Evidence into the specific relationship between maximum strength (peak torque), rate of torque development, and strength endurance is lacking in the sports medicine community.

Parameters of Muscular Strength

One of the primary functions of skeletal muscle is to produce force (Kaminski & Hartsell, 2002) in order to facilitate skeletal movement, joint stability, and postural control (Hamill & Knutzen, 2003) Clinically, healthcare professionals describe the ability to create force (i.e. active tension) as strength (Oatis, 2004). In this context muscular strength can be defined as the capacity of a muscle(s) to generate active tension and to produce force (Hislop & Perrine, 1967) during a single voluntary contraction (Knapik & Ramos, 1980). The tendons of that muscle (s) transmit the force (resulting from active tension) to the bone(s) at an axis resulting in motion or stabilization about a joint (Fukunaga, Ichinose, Ito, Kawakami, & Fukashiro, 1997). The prevailing theory describing how this active tension occurs is the sliding filament theory (Enoka, 2002; Hamill & Knutzen, 2003; Oatis, 2004), first proposed by Huxley (Huxley, 2004).

The theory is described as the active tension created by a contracting muscle result from the formation of cross bridges between the myosin (thick myofilaments) heads and actin (thin myofilaments) chain (Enoka, 2002; Hamill & Knutzen, 2003; Oatis, 2004). This bond results in the myosin heads cyclically attaching to the actin filament and drawing the actin filaments across (Hamill & Knutzen, 2003; Herzog, Leonard, Joumaa, & Mehta, 2008; Oatis, 2004). The tension created by the contraction is dependent upon the number of cross bridges formed between the two filaments (Oatis, 2004). Factors dictating the number of cross bridges formed include the amount of myosin and actin molecules, and the frequency of the stimulus to form the cross bridges (Oatis, 2004). Triggering this event (i.e. active tension) is the occurrence of an action potential received by the muscle fibers from the motor neuron. This action potential stimulates all of the muscle fibers associated with that particular motor neuron (termed the all or none principle). Upon arrival of this action potential to the neuromuscular junction (also termed motor endplate) (Hamill & Knutzen, 2003), which lies near the center of the fiber at the synapse, a series of chemical reactions occur resulting in the release of acetylcholine (ACH) (Hamill & Knutzen, 2003; Pearson, 2004). The release of ACH causes the membrane of the fibers to become more permeable and causes a decrease in the resting potential of the fiber membrane (Hamill & Knutzen, 2003; Pearson, 2004). This leads to an exchange of sodium (NA^+) and potassium (K^+) thru the pores of the fiber membrane resulting in depolarization (due to NA^+) and repolarization (Hamill & Knutzen, 2003; Pearson, 2004). This depolarization triggers a release of calcium, which binds to troponin (a regulatory protein) (Oatis, 2004). This binding of calcium and troponin leads to the formation of the myosin and action cross bridges, resulting in the generation of active tension and force production. The attachment and detachment cycle of the cross bridge is powered by the energy liberated thru the hydrolysis of one molecule of adenosinetriphosphate (ATP) (Herzog, et al., 2008; Pearson, 2004). Although the muscles of the human body produce force linearly, motion at a joint is generally rotary moving an object about an axis (Hogrel et al., 2007). Therefore, when assessing intact joint actions (i.e. in vivo), strength is best quantified in terms of torque (Hogrel, et al., 2007), which is the propensity of force to move an object about an axis or fulcrum and is termed moment (or torque) (Krevolin, Pandy, & Pearce, 2004), and expressed through the following equation:

T= moment arm [m] x force [N]..................................Equation (2.1)

where Torque (T) is equal to the length of the moment arm in meters [m] multiplied by the force produced in Newtons [N] (Lieber & Bodine-Fowler, 1993; Oatis, 2004). To account for conditions in which the force application is at an angle (θ) relative to the axis of the moment arm (Lieber & Bodine-Fowler, 1993), it is necessary to expand equation one as follows:

T = |moment arm [m]| · |force [N]| · sinθ....................Equation (2.2)

where the vertical bars about the moment arm and force quantities signify vector magnitudes, and the θ is the angle between the direction of force application and the fulcrum (Lieber & Bodine-Fowler, 1993).

Maximum Strength

Muscular strength is comprised of three principle components or parameters: a) maximum strength (Smax), b) rate of force development, and c) strength endurance (SE) (Castro-Piñero, et al., 2010; Mebes, et al., 2008). Peak torque or maximum strength is the highest amount of force produced during a voluntary contraction under isometric, eccentric, and concentric conditions

(Mebes, et al., 2008). Several factors are believed to be determents of peak force production and include age, muscle architecture, muscle length-tension relationship, load-velocity relationship, muscle fiber type, and lever arm length (Gaines & Talbot, 1999; Knapik, et al., 1983a; Lieber & Friden, 2000, 2001). Of the aforementioned factors, the clinicians can augment three of those during strength evaluations: muscle length-tension relationship, load-velocity relationship, and moment arm length.

Muscle Length-tension Relationship. As previously stated, strength is a function of the number of cross bridges formed between the myosin and actin filaments within the sarcomeres, therefore changes in the proximity of the actin and myosin chains can influences a muscle's ability to produce force (Oatis, 2004). According to the length-tension relationship when the myosin and actin reach or exceed their overlapping capabilities, a reduction in contractile tension ensues (Hamill & Knutzen, 2003). Similarly, when the muscle is elongated past their overlapping capabilities there is a reduction in contractile tension (Hamill & Knutzen, 2003; Oatis, 2004). The reduction in contractile tension during these two scenarios is due to the formation of fewer cross bridges as a result of incomplete activations of the cross bridges (shortening) or cross bridge slippage (lengthening) (Hamill & Knutzen, 2003). As a result, when the full length of actin strands at each end of the sacromere are in contact with the myosin molecules (i.e. the resting length), the sacromere is capable of its maximum contractile force (Oatis, 2004). However, while diminished contractile tension results during lengthening conditions exceeding the muscle's resting length (Oatis, 2004), the passive components (parallel and series elastic components) provide force against the stretch (storing elastic energy) and increase the overall tension of the entire system (Hamill & Knutzen, 2003; Oatis, 2004). Therefore, the optimal muscle length is one slightly beyond the resting length allowing for the use of the stored elastic energy from the passive components (Hamill & Knutzen, 2003). This phenomenon gives support for the practice of placing the muscle(s) on a stretch prior to using the muscle(s) for a joint action (Hamill & Knutzen, 2003).

Load-Velocity Relationship. The load-velocity relationship demonstrates a fundamental biomechanical principle, that the maximum force or torque generated by a muscle is a function of the velocity (Lieber & Bodine-Fowler, 1993). Therefore, during isometric muscle contractions the maximum force or torque production is theoretically greater than that of a concentric contraction because the velocity of an isometric contraction is equal to zero. The relationship between force produced and velocity achieved is an inverse one so as velocity increases during a concentric contraction the muscle ability to create maximum force diminishes. In short, slower concentric contractions have a greater force or torque potential than those performed at faster concentric velocities. In this context the reverse is also evident, that a muscles contraction velocity is dependent upon the load resisting the muscle , as the load increases the muscles contraction velocities responds in an inverse manner (decreases). As the load applied to a muscle or groups of muscles increases, the muscle reaches a point at which the external load is greater than its force generating capacity (Lieber & Bodine-Fowler, 1993). This results in the eccentric phase of a muscular contraction in which the muscle as earlier stated begins to lengthen. During eccentric contractions, the muscle resists the imposed stretch placed upon it because of external load. The resistance of the muscle during this phase acts as a braking mechanism decelerating the load or limb such as during human movement (Lieber & Bodine-Fowler, 1993). As the velocity of the eccentric action increases the muscles creates greater tension in order to resist elongation. This continues until the muscle reaches the point in which it can no longer control the movement of the external load, resulting in a plateau in force production (Hamill & Knutzen, 2003). The force potential of eccentric contraction is greater than that produced by either isometric or concentric contractions (Oatis, 2004). According to estimations, eccentric strength is 1.5 to 2.0 times greater than that of concentric contractions (Oatis, 2004). The increased force potential of eccentric phase contractions may be contributed to the amount of force needed to disassociate actin-myosin cross bridges and or the elastic properties and stiffness of the muscle-tendon unit (Kaminski & Hartsell, 2002).

Muscle Moment Arm Length. As previously discussed, the propensity of force to move an object about an axis or fulcrum is termed moment (or torque) (Krevolin, et al., 2004). The moment produced about a joint is the result of the product of force and moment arm length (see equations 1 and 2). In terms of an intact joint, the muscles ability to create torque about a joint is dependent upon the muscles force generating capacity and length of the muscle's moment arm. In this context, the muscle moment arm is the perpendicular distance from the line of action (force) to the instantaneous center of rotation (Lieber & Bodine-

Fowler, 1993). The use of the term instantaneous draws note to the fact that not all joints have a singular center of rotation (Krevolin, et al., 2004; Lieber & Bodine-Fowler, 1993). As seen in many intact joint articulations within the human body (e.g. tibiofemoral joint), the centers of rotation are dependent upon the angular positioning of the joint (Krevolin, et al., 2004; Lieber & Bodine-Fowler, 1993). Calculation of the length of a muscle's moment arm is done thru the following equation:

$l = d \cdot \sin \theta$ .... Equation (2.3)

where l is the moment arm, d is the distance between the muscle's attachment and the joint's axis of rotation, and sin θ is the angle of application (Oatis, 2004). According to equation three, moment arm length is a function of the product of distance and joint positioning; this would lead one to assume that maximum torque output at a specific joint occurs when the moment arm is at its greatest length. However, in many cases when the muscle moment arm is at maximum length, there is a reduction in maximum contractile force because the muscle is not in an elongated state eliminating the use of the stretch-shortening mechanism (Oatis, 2004). Therefore, variations in the muscle mechanical advantage in terms of moment arm length, especially during isometric evaluations, potentially could lend to alterations in torque production when assessing strength in resting or near resting position. In addition, alterations in torque production can occur if a muscle crosses two joints, because its moment arm can be dependent on the position of both joints its crossing.

Rate of Torque (or Force) Development

Although researchers have assessed the reliability (Clark, et al., 2006; Impellizzeri, Bizzini, Rampinini, Cereda, & Maffiuletti, 2008; Kollock, et al., 2010; Maffiuletti, Bizzini, Desbrosses, Babault, & Munzinger, 2007; Scott, et al., 2004; Symons, et al., 2005) and made comparisons among the modes of testing (Anderson, 1991; Jameson, et al., 1997; Knapik, et al., 1983a; Knapik, et al., 1983b; Runnels, Bemben, Anderson, & Bemben, 2005), most evaluate maximum strength (peak torque) and give little attention to other parameters of strength. In sports and other strenuous activities, the ability to produce explosive muscular strength and to sustain it may be more important to performance and the susceptibility to re-injury following rehabilitation. The second strength parameter, the rate of torque development (RTD) is the rate of rise in joint moment at the onset of a muscle contraction (Aagaard, et al., 2002) and expressed thru the equation 5:

$$RTD = \Delta Torque/\Delta Time \quad \text{..Equation (2.4)}$$

According to Aagaard et al. (2002), RTD has vital functional significance to rapid and forceful muscle contractions. Scientists assess the RTD parameter at time-periods ≤ 300 millisecond (ms) (Aagaard, et al., 2002) because the time allowed to exert force in sports involving sprint running, jumping, and other explosive types of movements usually is very limited, occurring within 50 to 250 ms (Andersen & Aagaard, 2006). This is in contrast to the time needed to attain maximum muscular strength, which typically occurs at time-periods > 300 ms

(Aagaard, et al., 2002; Andersen & Aagaard, 2006). Physiological factors affecting the RTD include maximal muscle strength, muscle cross sectional area, muscle fiber types, and neural drive to the muscle (Andersen & Aagaard, 2006). In association with RTD, researchers also report the total contractile impulse (TCI) as an important biomechanical aspect of strength (Aagaard, et al., 2002; Baker, Wilson, & Carlyon, 1994). Graphically, the TCI is represented as the area under the moment-time curve and is numerically expressed as the product of the average torque in Newton·meters (Nm) and time (seconds [s]) in seconds [Nm_{mean} x s] (Enoka, 2002). The TCI is representative of the entire time history of the contraction. The TCI is identical to the kinetic impulse or momentum reached under dynamic conditions (Aagaard, et al., 2002), and expressed thru equation 6:

$$TCI = \int Moment\, dt \quad \text{Equation (2.5)}$$

Strength Endurance

In open kinetic chain strength evaluations, endurance is the ability of a muscle(s) to sustain a maximal contraction for a prolonged period of time (≈20-30 seconds) or the ability to perform repeated contractions (20-40 repetitions) (Brown, 2000). Based on anaerobic capacity, strength endurance (SE) is the resistance to fatigue under anaerobic strength conditions (Mebes, et al., 2008). In this scenario, fatigue is a breakdown of common physiological functions that produce reductions in Smax generating capacity (Asmussen, 1952; Bilcheck, Maresh, & Kraemer, 1992) developing gradually after the onset of the activity.

(Enoka & Duchateau, 2008) Therefore, within this context fatigue is not the perceived weakness of a muscle (s) or the endpoint of a task performance (exhaustion) (Enoka, 2002), but rather the decline in maximum strength during a single contraction or numerous contractions over a prolonged time period. During tasks that involve a sustained maximal contraction, the decline in performance parallels the increase in fatigue (Enoka & Duchateau, 2008), Fatigue does not occur due to the impairment of a single process, instead it is the results of numerous mechanisms (Enoka, 2002) contributing to the overall decrement of the task performance. These mechanisms can be sensory or motor and differ in contribution from one condition to another, which is termed task dependency (Enoka, 2002), During task performance, the requirements of the activity (e.g. amount of muscle force and duration of activity) stress (potentially impairing) a range of physiological processes associated with the performance (Enoka, 2002). The physiological processes impaired during prolonged performance of a task, resulting in fatigue include primary motor cortex activation (Enoka, 2002), supraspinal drive to motoneurons (Bilcheck, et al., 1992; Enoka, 2002; Westerblad & Allen, 2002), the motor units and muscles activated (Enoka, 2002), neuromuscular propagation (Enoka, 2002), and muscle fiber excitation-contraction coupling (Bilcheck, et al., 1992; Enoka, 2002; Westerblad & Allen, 2002). Other physiological processes potentially impaired are metabolic substrate availability (e.g. glycogen), intracellular milieu, contractile apparatus, and blood flow to muscles (Enoka, 2002), Performance associated variables dictating the distribution of stress among the individual processes include performer motivation level, neural strategy(s) adopted during performance, and performance intensity and duration (Enoka, 2002).

Fatigue has two principle task dependent components referred to as central or peripheral (level of the muscle fibers) fatigue (Enoka & Duchateau, 2008; Enoka & Stuart, 1992; Nordlund, Thorstensson, & Cresswell, 2004). During central fatigue, there is a decline in the supraspinal "drive" of the motoneurons or direct inhibition of motoneurons (Westerblad & Allen, 2002). These occurrences give rise to altered motoneurons excitability or inability of the motor nerve to conduct a repetitive action potential to the presynaptic side of the neuromuscular junction (Bilcheck, et al., 1992; Green, 1987). Central fatigue is therefore an activity-induced inability to activate a muscle voluntarily (Nordlund, et al., 2004) due to limitations of the central nervous system (MacIntosh & Rassier, 2002). In short, the muscle is capable of greater output, but the central nervous system is unable to activate the appropriate motor pathways (MacIntosh & Rassier, 2002). In contrast, peripheral fatigue is associated with a decreased ability of the muscle to produce force during the activity because of alterations within the actual muscle cell (Bilcheck, et al., 1992). The alteration to the muscle cell due to peripheral fatigue renders the muscle incapable of responding in the manner prior to the task that gave rise to the fatigued state (MacIntosh & Rassier, 2002). There are two main mechanisms within the muscle cell potentially affected during peripheral fatigue (i.e. excitation and or activation mechanisms) (Bilcheck, et al., 1992). The impact of fatigue to one or more of these mechanisms results in a reduction of calcium and/or calcium binding sensitivity during the muscular contraction (Westerblad & Allen, 2002) therefore reducing the rate of force reproduction (Bilcheck, et al., 1992) .

Fatigue, whether central or peripheral, negatively affects performance. Central fatigue mechanisms may work to impair efferent signals from the central nervous system, while peripheral mechanisms perhaps result in an inability of the muscle cell to respond to efferent information proceeding from the central nervous system (Bilcheck, et al., 1992; Westerblad & Allen, 2002). Either result in a retardation of the neuromuscular response or control mechanisms lending to less than adequate postural control and functional joint stability during athletic participation. Due to the negative impact of fatigue on the performance, measures of SE are essential in determining an athlete's return-to-play status.

Clinically healthcare professionals can determine isometric SE of a muscle or group of muscles with a fatigue-index (FI) ratio (Surakka, Romberg, Ruutiainen, Aunola, et al., 2004; Surakka, Romberg, Ruutiainen, Virtanen, et al., 2004). FI defined here is the ratio between the observed area under the force-time curve over a prolonged period of time (e.g. 20-30 s) and the hypothetical area under the force-time curve that observers would have measured if the participant maintained maximal force without fatigue throughout the entire contraction time (Djaldetti, Ziv, Achiron, & Melamed, 1996). Djaldetti et al. (1996) defined the FI as the ratio between the integral of muscle strength decay over time. Through isokinetics, clinicians assess endurance between velocities of 180°s and 240°/s, with individuals usually performing 20 to 30 reps. Clinicians comparing the repetitions performed bilaterally or comparing the work performed during the initial 5 repetitions (or initial 25%) to the work performed at the end of the testing bout (Brown, 2000). The latter allows the use of a fatigue index, which in the case of isokinetic evaluations is the percent change from the beginning to the end an endurance test bout (Brown, 2000). In terms of determining the return to play status of an athlete, research into the evaluation of the capacity of the muscle (s) of the involved limb to sustain a contraction or perform repeated repetitions over a prolonged period (≈20-30 seconds) is limited.

Reliability of Dynametric Strength Devices

Conventional Isokinetic Dynamometry

Within the literature, researchers have assessed the reliability of various dynametric instruments (isometric and isokinetic) in measuring maximum strength (Clark, et al., 2006; Impellizzeri, et al., 2008; Kollock, et al., 2010; Maffiuletti, et al., 2007; Roebroeck, Harlaar, & Lankhorst, 1998; Scott, et al., 2004; Symons, et al., 2005; Tiffreau, Ledoux, Eymard, Thevenon, & Hogrel, 2007). Overall, computer-based strength evaluations have been proven reliable as methods for assessing muscular strength (Aydog, Aydog, Cakci, & Doral, 2004; Eng, Kim, & Macintyre, 2002; Kollock, et al., 2010; Scott, et al., 2004; Symons, et al., 2005). Isokinetic instrumentation is arguable one of the most reliable computer-based strength evaluation device reported within the literature (Clark, et al., 2006; Impellizzeri, et al., 2008; Maffiuletti, et al., 2007; Symons, et al., 2005; Tiffreau, et al., 2007). Following orthopaedic rehabilitation of patients who have undergone a surgical procedure, such as a anterior cruciate ligament (ACL) reconstruction, healthcare practitioners traditionally utilize isokinetic strength testing to assess and compare (i.e. limb symmetry) the lower extremity strength capacity of the surgical limb to the non-surgical limb (Ostenberg, et al., 1998). Isokinetic dynamometry is arguably, the gold standard in strength assessments due to its validity and ability to assess contralateral (Andrade, Cohen, Picarro, & da Silva, 2002) and bilateral strength differences.

Isokinetic testing assesses muscular strength at a constant velocity (Brown, 2000; Deighan, 2003; Hill, 1996; Purkayastha, et al., 2006; Schmitz & Westwood, 2001) allowing for velocity augmentation only during the initial test set-up. Some commercial isokinetic dynamometers are capable of concentric velocities of 500°/s and eccentric velocities of 300°/s (BMS, 2007). Isokinetic testing is accommodating to the patient, so it theoretically allows for maximal muscle loading and mechanical output throughout the entire range of motion at a selected joint (Brown, 2000; Deighan, 2003; Hill, 1996; Purkayastha, et al., 2006; Schmitz & Westwood, 2001). However, it is reported that maximal muscle loading throughout the entire joint range of motion creates excessive shear force during certain single joint movements increasing the risk of injury during testing (Dvir, 1996).

Isokinetic dynamometry has undergone numerous reliability evaluations into the ability to assess lower extremity muscular strength, specifically maximum strength (i.e. peak force). Eng et al. (2002) assessed the reliability of the Kin Com Isokinetic Dynamometer (Chattanooga Group Inc, Chicago, IL) in concentric mode for hip extension and flexion, and found this device to have excellent inter-session and intra-session using intra-class correlation coefficients (ICCs) (Eng, et al., 2002). The reported inter-session reliability for hip extension ranged from .97 to .98 and .98 to .95 for hip flexion, while the intra-session reliability ranged from .97 to .96 for hip extension and .98 to .92 for hip flexion (Eng, et al., 2002). Researchers have reported similar findings at the knee and ankle joints. In a study conducted by Symons et al. (2005) in which a Biodex System 3 (Biodex Medical Inc., Shirley, NY) was used, ICC values ranged from 0.88 to 0.92 for inter-session isokinetic knee extension testing protocol at 90°/s (Symons, et al., 2005). Lastly, at the ankle joint, Aydog et al. (2004) investigated the intra-tester and inter-tester reliability of isokinetic ankle inversion and eversion-strength at 60 and 180°/s, using the Biodex Dynamometer. The intra-tester and inter-tester ICC values for ankle inversion ranged from 0.92-0.96, while the eversion values ranged from 0.87 to 0.94 for peak torque assessments (Aydog, et al., 2004).

Although the findings within the literature display adequate reliability, access to isokinetic dynamometry is often limited to larger outpatient clinics or hospital physical rehabilitation facilities. Primarily due to the cost (≈$50,000-$60,000) other factors such as its size and lack of portability are also limitations. In order to increase clinician access to objective computer based strength techniques some have proposed the use of less sophisticated types of dynamometers that are more cost effective (Bohannon, 1990; Scott, et al., 2004) and portable (Bohannon, 1990; Hill, 1996; Martin, et al., 2006), such as advanced isometrics using hand-held (HHD) and portable fixed dynamometry (PFD).

Advanced Isometric Dynamometry: The Use of PFD

Due to the impracticality of isokinetic dynamometry in some settings, the use of small and portable forms of dynamometry such as isometric HHD has become popular. This device has grown in popularity because of its simplicity, portability, objectivity, and its ability to detect deficits in strength (Li et al., 2006; Taylor, Dodd, & Graham, 2004; Wang, Normile, & Lawshe, 2006). Multiple investigations have used HHD to assess baseline strength measures and to evaluate the relationship between hip strength and certain lower extremity injuries such as lateral ankle sprains (LAS), PFPS, and ITBS (Fredericson, et al., 2000; Friel, McLean, Myers, & Caceres, 2006; Lanning et al., 2006; McHugh, et al., 2006; Tyler, McHugh, Mirabella, Mullaney, & Nicholas, 2006; Tyler, Nicholas, et al., 2006). Furthermore, the literature presents similar findings as isokinetic instrumentation in terms of reliability displaying minimal variation between measures obtained by the same tester (intra-rater reliability) and also between those of different testers (inter-rater reliability) when standardized testing procedures are utilized (Krause, et al., 2007; Scott, et al., 2004; Wang, et al., 2006).

In a study performed by Krause et al. (2007), they reported intra-rater ICC values for hip abduction ranging from .91-.93 and .79 to .89 for hip adduction (Krause, et al., 2007). This group also reported inter-rater ICC values ranging from .68 to .73 for hip abduction and .62 to .82 for hip adduction (Krause, et al., 2007). In a study conducted by Scott et al. (2004) in which the researchers evaluated 15 healthy participants it was reported that HHD displayed intra-rater ICC values ranging from 0.67 to 0.81 for the assessment of the hip flexors, abductors, and extensors (Scott, et al., 2004). Reinking et al. (1996) observed that HHD was a reliable means of assessing the knee extensors. The group reported intra-rater ICCs of 0.92 and standard error of measure (SEM) values at 4.3 Newtons (Reinking et al., 1996).

However, while this type of dynamometry allows the clinician portability and is less expensive than conventional isokinetic devices, it is not without its disadvantages (Ford-Smith, Wyman, Elswick, & Fernandez, 2001; Martin, et al., 2006). The high force demands needed by clinicians to counter the force produced by the patient (patient-tester force-counter-force) have shown to be problematic when assessing the larger muscle groups such as the quadriceps femoris (Bohannon, 1997a; Martin, et al., 2006; Nadler et al., 2000). This inability to stabilize against larger muscle groups could result in a great deal of variability between trials (Kollock, et al., 2010).

An alternative method of evaluating muscular strength is through isometric portable fixed dynamometry (PFD). PFD is a load cell, strain gauge, or force transducer that is mounted, embedded, or attached to a fixed structure to remove the tester-patient interaction at the site of force application. Researchers have introduced several PFD instruments in the literature and evaluated them for reliability (Nadler, Malanga, et al., 2000; Scott, et al., 2004). Nadler et al. (2000) assessed the test-retest reliability of a dynamometer anchoring station (DAS) using 10 subjects between the ages of 25 to 35. He reported finding high intra-session ICC values of .95 and 98 (hip abduction maximum and mean) and .94 and .98 (hip extension maximum and mean) (Nadler, DePrince, et al., 2000). A later study conducted by Scott et al. (Scott, et al., 2004) compared the intra and inter-rater reliability of the Nadler (2000) portable DAS to a HHD. The group used two examiners were to evaluate hip extension, flexion, and abduction in 15 healthy participants between the ages of 23 and 44. The researchers reported inter-rater ICCs for the average peak measures ranging from 0.84 to 0.92 for hip flexors, 0.69 to 0.88 for the hip abductors, and 0.56 to 0.80 for hip extensors. The researchers also reported that the intra-rater ICCs ranging from 0.59 to 0.89 for tester A, and from 0.72 to 0.89 for tester B, using the DAS, with the reliability for HHD across all tested muscle groups, ranged from 0.67 to 0.81 (Scott, et al., 2004).

Kollock, et al. (2010) examined the reliability of a portable fixed dynamometer (PFD) to assess hip abductor, hip adductor, hip internal rotator, hip external rotator, knee extensor, and knee flexor strength. The study was conducted in two distinct phases (Phase 1: mass testing and Phase 2: individual non-mass testing). The phase one intra-session values for session 1, 2, and 3 ranged from (ICC = 0.88-0.99, SEM = 0.08-3.02 N), (ICC =0.85-0.99, SEM = 0.26-3.88 N) and (ICC = 0.92-0.96, SEM = 0.52-2.76 N), respectively for hip and knee strength. The phase one inter-session values ranged from (ICC = 0.57-0.95, SEM = 1.72-9.07 N) for hip and knee strength. The phase two intra-rater reliability values ranged from (ICC = 0.70-0.94, SEM = 1.42-9.20 N), while the inter-rater values ranged from (ICC = 0.69-0.88, SEM = 1.20-8.50 N) for hip and knee strength.

Regardless of type of computer-based muscular strength evaluation or mode of contraction assessed, it appears that the computer-based methods are a reliable means of assessing muscular strength. Evidence supports the use of computer-based isometric and isokinetic strength evaluations as a reliability means of assessing muscular strength at both the hip and knee (Eng, et al., 2002; Kollock, et al., 2010; Scott, et al., 2004; Symons, et al., 2005). Although each method presents some limitations, select methods such as isometric PFD may be feasible to include into PPE because of its portability, design, and set-up. The design and set-up of isometric PFD removes the tester-patient interaction at the site of force application negating the need for the tester to be able to exert an equivalent counter force to stabilize against patient contraction (Bohannon, 1997a; Martin, et al., 2006; Nadler, DePrince, et al., 2000). However, the zero-velocity test conditions during evaluations do not provide the concentric or eccentric strength details afforded with isokinetic testing. Although isokinetic testing has long been regarded in sports medicine arena as the optimal outcome measures following orthopedic rehabilitation researchers and clinicians have long recognized the limitations of a single joint fixed velocity evaluation in determining an individual's physical readiness following rehabilitation (Ostenberg, et al., 1998).

The Association of Isometric and Isokinetic Assessments

Although the findings within the literature are mixed, some earlier research conducted between 1980 and 2000 has reported observing very strong relationships (r = 0.70 to 0.89) between isometric Smax (often termed peak force) and lower (60°/s) to mid (180°/s) isokinetic velocities (Hill, 1996; Jameson, et al., 1997; Knapik, et al., 1983b). In a 1980's study conducted by Knapik, et al. (1983b), using sophisticated dynamometry for both isometric and isokinetic assessments at 36, 108, and 180°/s, the researchers reported *r*-values ranging from .71-.83 for knee extensor and .49-.80 for knee flexor strength, with the correlation being the strongest at the lower velocities. With the exception of the 0.49 r-value reported for knee flexor strength between isometric and isokinetic dynamometry at 180°/s, all other measures were greater than 0.70. Hill, et al. (1996) also reported very strong correlations (r = 0.70 to 0.89) in which 25 children (18 boys and 7 girls) between 9- 11 years of age were recruited. They assessed peak torque using a HHD and an isokinetic dynamometer at 60,120, and 180°/s. They observed that the highest correlations were at isokinetic strength at 60°/s with r^2 values ranging from .64-.66 for the knee extensors and .50-.61 for knee flexors. The researchers also reported that peak torque recorded with the HHD was significantly higher than peak torque values assessed using isokinetic dynamometry at all evaluated test velocities. These findings by Hill, et al. (1996) are supported by Murray, et al. (1980) in which a dynamometer (Cybex II, Division of Lumex Inc., Ronkonkoma, NY) was used for both the isometric and isokinetic assessment at 36°/s. Murray, et al. (1980) reported that mean maximum isokinetic peak torque values were significantly less than the mean maximum isometric torque at every joint position assessed. Knapik, et al. (1983a) also reported differences in peak torque values between different dynametric contraction modes. The researchers here reported that isometric peak torque values collected with a Cybex apparatus were generally higher than recorded values from the K-K isotonic device (JA Preston Corp, Clifton, NJ). The finding of higher isometric values versus either isokinetic or isotonic measures is not surprising given torque (or force)-velocity relationship described by Hill (1938).

While the previous researchers have reported a very strong association (*r* = 0.70 to 0.89) between isometric and isokinetic dynamometry Reinking, et al. (1996) evaluated 23 subjects and did not report similar findings. They reported that isometric and isokinetic values at 60°/s displayed moderate correlations (r = 0.30 to 0.49) with an *r*- value of 0.45 for the concentric phase and 0.43 for eccentric phase knee extensor strength. It should be noted however, that the isometrics were recorded using HHD which could have been affected by earlier described limitations such as the inability to stabilize against force produced by larger muscle groups. Martin, et al. (2006) reported an inability to stabilize against larger muscle groups. They evaluated force using a Biodex System 2 isokinetic dynamometer (in isometric mode) and HHD and reported that the HHD under-estimated force production by 14.5 Newtons [N] due to low tester strength and poor stabilization of the participants. However, other researchers using forms of PFD (e.g. mounted load cells or strain gauges) have reported similar findings. In a more recent study conducted by Requena, et al. (2009) evaluating 21 male soccer players in the First Estonia Soccer Division, it was reported that a moderate correlation (*r* =0.31) for the relationship of isometric and isokinetic peak torque at 180°/s. They observed a moderate correlation between isometric PT and isokinetic PT at 60°/s at the knee joint.

The relationship between isometric and isokinetic evaluations display a moderate to very strong correlation (r = 0.30 – 0.89). According to Knapik, et al. (1983b) and Hill, et al. (1996) the strength of the relationships increase as the isokinetic velocities decrease, which Hill, et al. (1996) contributes to a function of the force-velocity relationship. The force-velocity relationship may also be a contributing factor to the isometric peak torque as compared to isokinetic (Hill, 1938). Hand-held isometric devices may present issues with poor stabilization of participant resulting in an underestimation of torque values as compared to bigger more sophisticated dynamometry such as the Biodex System 2 (Martin, et al., 2006).

Functional Performance Testing

Single-joint computer-based muscular strength evaluations are valid (Drouin, Valovich-mcLeod, Shultz, Gansneder, & Perrin, 2004; Patterson & Spivey, 1992; Seger, Westing, Hanson, Karlson, & Ekblom, 1988; Tunstall, Mullineaux, & Vernon, 2005; Westblad, Svedenhag, & Rolf, 1996) and reliable (Aydog, et al., 2004; Eng, et al., 2002; Kollock, et al., 2010; Scott, et al., 2004; Symons, et al., 2005) means of assessing muscle function at particular joint. However one particular drawback is the lack of functionality of the movement pattern (i.e. single joint testing parameters) and velocity (i.e. constant throughout testing) (Andrade, et al., 2002). To help provide a more realistic representation of forces experienced during activities of daily living and sports or athletic participation are measures of functional performance (FPT), such as single limb hopping tasks (Clark, 2001). FPTs are popular because they normally require minimal materials (Hamilton, et al., 2008), space, time (Hamilton, et al., 2008), and personnel for test administration (Clark, 2001) making them ideal for use during PPEs and RTPs (Clark, 2001). FPTs are typically performed using a single limb protocol because of the ability to use of the uninjured extremity as control for within-subject bilateral comparisons (Clark, 2001; Hopper, et al., 2008). Furthermore, single leg hops allow the clinician to evaluate independently, the performance and stability of the involved lower limb, without the masking effects of the uninvolved limb such as with the vertical and standing broad jump tasks (Hopper, et al., 2008).

This use of single-limb hop tests also grants the clinicians a practical means of bilateral comparison and assessing limb symmetry using a limb symmetry index (LSI) ratio (Ostenberg, et al., 1998; Robinson & Nee, 2007). LSI ratios are useful in clinical settings where clinicians are not able to make comparisons to control groups. Researchers have suggested that a limb symmetry ratio of less than 85% may indicate an increased risk of the knee giving way during athletic performance (Barber, Noyes, Mangine, McCloskey, & Hartman, 1990; Hopper, et al., 2008). Clinicians can calculate LSI Ratio with the following equation:

LSI = (Involved/uninvolved) x 100....................................Equation (2.6)

LSI is equal to the distance of a hop(s), number of hops, or amount of time taken to perform the task over a set distance with the involved limb divided by the performance of the same task on the uninvolved limb. Although single limb hop tests allow for a point of comparison especially in the absence of baseline or normative data (Hopper, et al., 2008), double limb tasks such as with the vertical jump task have also been reported in the literature as valid and reliable (Locke & Sitler, 1997; Thomas, Fiatarone, & Fielding, 1996). Researchers have used a variety of double and single limb test batteries, which involve jumping, hopping in a straight line, and side-side hopping maneuvers (Gustavsson, et al., 2006; Hopper, et al., 2008; Itoh, et al., 1998; Keays, et al., 2003). The clinical value of functional tests relates to their effectiveness in providing an objective indicator of dynamic lower limb performance under simulated conditions (Hopper, et al., 2008).

Health-care practitioners can use FPTs to determine the return to play status of an athlete following orthopaedic rehabilitation from ACL reconstruction (Gustavsson, et al., 2006; Ostenberg, et al., 1998; Ross, Irrgang, Denegar, McCloy, & Unangst, 2002). Common single limb hopping tasks reported within the literature include the single leg hop for distance (SLHD), triple hop for distance (THD), the crossover hop for distance (CHD), and the 30-second hop test for endurance (30-HTE) (see appendix I. table 2.1) (Hopper, et al., 2008; Itoh, et al., 1998; Keays, et al., 2003; Ostenberg, et al., 1998). SLHD and THD tests are performed with the patient hopping horizontally for distance (Hamilton, et al., 2008; Ostenberg, et al., 1998). The SLHD test requires the individual to stand on one limb and hop, using a maximal effort, as far as possible and the total distance hopped is recorded (Keays, et al., 2003; Ostenberg, et al., 1998).

The THD test is performed in a similar manner, however instead of one hop the performer is asked to perform three hops (Keays, et al., 2003). Each hop is performed using a maximal effort. The total distance hopped across the three hops is recorded (Hamilton, et al., 2008). According to the findings within the literature, the THD has been reported as a valid predictor of lower-limb strength and power (Hamilton, et al., 2008). Researchers have also reported that the SLHD and THD tests are reliable (Booher, Hench, Worrell, & Stikeleather, 1993; Ross, Irrgang, et al., 2002). Ross, et al. (2002) reported inter-session intra-class correlation coefficients ($ICC_{[2, 3]}$) for the SLHD and THD test to be 0.92 and 0.97, with a standard error of measure (SEM) of 4.61 and 11.17 cm, respectively (Ross, Langford, et al., 2002). They also reported finding an $ICC_{[2, 3]}$ of 0.93 with a SEM of 17.74 cm for the CHD test. For the CHD test, the patient hops forward using a maximal effort on the same limb three consecutive times, with each hop crossing over a line (Ross, Langford, et al., 2002). Similar to the THD test, the total distance hopped across the three hops is recorded (Ross, Langford, et al., 2002). Although, this test is performed by hopping horizontally (such as with the THD) it adds another movement component that requires a change in limb direction, which according to some potentially places greater demands on the knee (Hopper, et al., 2008).

FPTs are also performed in a side-to-side manner such as with the 30-HTE. The 30-HTE test allows for evaluation of an athlete's lower limb endurance and ability to perform multiple hops within a specified area (normally 30-40 cm) over a 30-second period, which demands knee stability while developing fatigue

(Gustavsson, et al., 2006). Athletes must perform all jumps without touching the tape, or it is counted as an error. If 25% or more of the jumps are counted as errors, the test will be performed after a 3-minute rest period (Gustavsson, et al., 2006). Gustavsson, et al. (2006) reported that the 30 second lateral hop test was a reliable measure of functional performance with ICC values 0.87 and 0.93 with an methodological error measure of 4.8 and 3.2 cm, respectively.

According to the literature, FPTs appear to be a reliable measure for assessing lower limb such as strength and power (Booher, et al., 1993; Gustavsson, et al., 2006; Ross, Langford, et al., 2002). The use of FPT has been proposed for use in helping determining an athlete's return-to-play status and while their use is not been reported in PPEs, minimal materials (Hamilton, et al., 2008) and time of test administration (Clark, 2001) may provide for a low cost muscular strength assessment battery. In the PPE and RTP scenario, health-care providers can use FPT batteries to help identify an athlete's ability to tolerate the physical demands of athletic competition (Clark, 2001). Although, single limb hop tests are not truly sports specific they do simulate the forces encountered during competitive situations (Creighton, et al., 2010). The use of single limb FPTs have been suggested within the literature because they allow the clinician the ability to use the uninvolved limb as a control or basis of comparison in the absence of baseline or normative data (Clark, 2001; Hopper, et al., 2008).

The Association of Dynametric Evaluations to FPT

Clinically, the use of FPTs represents a more time efficient and cost method of assessing muscle function versus isokinetic instrumentation (Clark, 2001; Hamilton, et al., 2008). However, these tests (FPTs and isokinetic testing) represent uniquely different methodological approaches (i.e. integration versus isolation) to evaluating muscular function. FPTs assess the function of the entire lower limb in an integrated manner encompassing strength, power, neuromuscular coordination, and stability across multiple joints (Docherty, et al., 2005; Hamilton, et al., 2008; Keays, et al., 2003). All of which is occurring at varied movement velocities. In contrast, isokinetic evaluations provide detailed information about a selected muscle group's ability to move a limb about the joint. Isokinetic instrumentation forces a muscle to contract at a constant or fixed velocity, regardless of muscular force out-put during limb movement (Brown, 2000; Deighan, 2003; Hill, 1996; Purkayastha, et al., 2006; Schmitz & Westwood, 2001). The research findings within the literature point to strong to very strong relationships between certain FPTs and isokinetic testing at the knee extensors and flexors (Bjorklund, et al., 2006; Hamilton, et al., 2008; Kovaleski, Heitman, Andrew, Gurchiek, & Pearsall Iv, 2001).

Bjorklund, et al (2006) evaluated the relationship between isokinetic muscular strength and criterion-based testing. This criterion-based test (Test for Athletes with Knee injuries [TAK]), was used to assess the functional ability of athletes with knee injuries. The study consisted of 59 patients and each patient represented one of three groups: a) ACL reconstructed (N=31), b) ACL-injured non-reconstructed (N=14), or c) healthy athletes (N=14). The TAK consisted of eight tests emphasizing strength, stability, springiness, and endurance: jogging straight forward, running straight forward, one leg standing with flexed knee, one leg rising task, squatting down with weight distributed equally, single leg hop for distance, one leg vertical jump, and crossover one leg hop task. The researchers used the kappa coefficients (κ) to assess the reliability of the TAK. The κ - values ranged from 0.62-0.78 (moderate correlation) for the inter-rater-reliability and from 0.43-0.65 (fair to moderate correlation) for the intra-rater reliability. The researchers used a Spearman's Rho (r_s) to assess the correlation between the deficiency of the functional capacity (as per the TAK) and isokinetic quadriceps' strength. They reported moderate correlations (r_s = 0.61-0.73) between the TAK and isokinetic quadriceps strength measured at 120°/s with the exception of both the jogging and running straight forward which displayed r_s - values between 0.34-0.52. The highest r_s –values reported were for the one leg rising task (0.73), squatting with weight distributed equally (0.69), and the one leg vertical jump task (0.68). For the relationship between isokinetics at 180°/s and the TAK the r_s –values ranged from 0.30 to 0.63 with the highest value reported for the one leg rising task (Bjorklund, et al., 2006).

Ostenberg, et al. (1998) evaluated isokinetic knee extensor (KE) strength (velocity = 60 and 180°/s) and its association to functional performance in 101 female soccer athletes and reported no significant correlations. However, they did report a moderate relationship between FPTs and isokinetic testing. The functional performance tasks assessed included the one leg hop for distance, triple jump, vertical jump, one leg rising, and the square hop test for endurance.

The researchers reported *r*- values between 0.30 and 0.31 for the association of isokinetic KE strength at 60°/s and functional performance and *r*-values between 0.42 and 0.46 for the relationship of isokinetic KE strength at 180°/s and functional performance. The measures of functional performance that displayed the strongest association with isokinetic KE strength at 180°/s were the one leg hop for distance (*r* =0.42) and triple jump (hop) for distance (*r*=0.46). Reporting dissimilar findings was an earlier study by Kovaleski, et al. (2001). Their study consisted of 30 uninjured males (N=15) and females (N=15). The researchers reported strong correlations (*r* = 0.50 to 0.69) between isokinetic KE at 60°/s and single leg hop (*r* =.623) as compared to Ostenberg et al. (1998) reports for the single leg hop (*r* = 0.30). However, Ostenberg, et al. (1998) reported using r-values corrected for weight, height, and age, which may account for some of the difference.

Kovaleski, et al. (Kovaleski, et al., 2001) also reported observing moderate relationships between isokinetic KE at 60°/s and vertical jump (*r* =.327). Tsiokanos, et al. (2002) however did not report a similar relationship using velocities of 120°/s and 180°/s. In their investigation, they evaluated the association of isokinetic KE strength and vertical jump in 29 male physical education students. The researchers reported *r* - values of .64 for vertical jump height and isokinetic torque at 180°/s and 0.85 for vertical jump work performed and isokinetic torque at 120°/s. These findings were duplicated by Hamilton et al. (2008) who evaluated 40 National Collegiate Athletic Association (NCAA) Division I men's and women's soccer student-athletes and found that isokinetic torque assessed at 60 and 180°/s for KE and KF displayed significantly (*p*<.01) large correlations with the vertical jump test (*r* =0.67- 0.77). The group also reported observing *r*-values ranging from 0.70-0.77 for the THD. From these findings, the investigators concluded that THD was a valid predictor of muscular strength and power in soccer populations. The investigators further indicated that the strong relationship between isokinetic testing and THD in their study supports a relationship between open kinetic chain and closed kinetic chain muscle performance.

Similar findings comparing strength indices (i.e. [injured/uninjured side] x 100) to the THD have also been reported. Keays, et al. (2003) reported that prior to ACL surgical repair patients isokinetic quadriceps strength indices assessed at 60°/s and 120°/s were significantly correlated (*r* = 0.53 - 0.59) to the single and triple leg hop tests. They also found strong to very strong significant correlations (r=0.61-0.74) for post-surgical strength indices and functional performance. The investigators concluded that the results could indicate that strength correlates stronger with FPTs in the stable than unstable knee. They further concluded that post-operatively, the surgical restoration of joint stability would be reflected in a stronger relationship between knee extensor strength and FPTs in ACL reconstructed knees. In a recent study, Tveter & Holm (2010) reported that knee extensor and flexor strength displayed a strong correlation with hop length. The investigators examined 341 school-aged children between 7-12 years of age, and asked the children to jump in a long serial fashion across a 61 cm wide and 6 m long walkway. Hop length (defined as the measure in cm from the center of the heel of the one footfall to the center of the heel of the next footfall of the same foot) was calculated by averaging the lengths of each hop. The investigators reported that hamstring and quadriceps strength assessed at isokinetic velocities of 60 and 240°/s showed a strong relationship to hop length (r = 0.63 – 0.68), with quadriceps strength measures at 240°/s displaying the highest values. They note that the strength values used in the analysis were measures of work in joules and not purely torque values.

Baker, et al. (1994) also evaluated functional performance in terms of work performed. Strength however in this study was not evaluated through isokinetic dynamometry, but rather Isometrically and data was collected for rate of force development (RFD) and total contractile impulse (TCI). They reported observing that RFD and TCI displayed a trivial to strong relationship to functional performance. They examined 22 males with a minimum six months previous weight training experience and found that isometric RFD during a unilateral leg extension prior to a 12 week strength training program had trivial to moderate correlations with vertical jump height ($r = 0.098$) and work in joules (r= [-.344]). They observed that TCI during a unilateral leg extension displayed a moderate to strong correlation with vertical jump height ($r = 0.39$) and work output ($r = 0.518$) (Baker, et al., 1994). Jameson et al (1997) also used isometric methods in studying this relationship between computer-based strength measures and FPTs. They reported that isometric peak force assessed at the knee extensors was moderately correlated ($r = 0.54$) with the one-leg vertical jump peak force measures. Additionally, they also reported that isokinetics moderately correlated with one-leg vertical jump peak force. Finally, Anderson, et al. (1991) who evaluated male varsity athletes (N=39) from five different sports reported that isometric and isokinetic peak force assessed at the knee flexors and extensors did not predict vertical jump height.

According to the findings within the literature, the reports are controversial with some reporting moderate correlations, while others have reported finding strong to very strong associations between the two methods. However, the research findings within the literature point to moderate to very strong relationships between isokinetic testing (at the knee extensors and flexors) assessed at various velocities and single-limb hop tests such as the SLHD and THD (Hamilton, et al., 2008; Ostenberg, et al., 1998). Similar results have been reported comparing strength indices and FPTs LSIs (Keays, et al., 2003). These reports of strong to very strong correlations appear to be consent across groups tested (healthy, children, athletes, and ACL reconstruction patients) when comparing isokinetic testing to the SLHD or THD. Investigations comparing isometric computer-based methods and FPTs are limited, with the available literature reporting low to moderate relationship between the methods (Baker, et al., 1994; Jameson, et al., 1997).

Summary

In summary, lower extremities injuries are common within athletic and sports settings (Agel, Evans, Dick, Putukian, & Marshall, 2007; Dick, Putukian, Agel, Evans, & Marshall, 2007). In response to these reports, researchers have begun trying to identify the mechanisms and factors associated to lower limb injuries (Croisier, et al., 2008; Engebretsen, et al., 2010; Powers, 2003; Souza & Powers, 2009b; Woods, et al., 2004). One potential risk factor reported within the literature is insufficient or decreased lower extremity muscular strength at the trunk, hip, and thigh (Fredericson, et al., 2000; Souza & Powers, 2009b; Tyler, et al., 2001). The use of muscular strength assessments during PPEs (Nadler, Malanga, et al., 2000; Scott, et al., 2004; Tyler, et al., 2001) and RTPs (Augustsson, et al., 2004; Best & Brolinson, 2005; Hopper, et al., 2008; Neeter, et al., 2006) may help to identify athletes with bilateral and agonist-antagonist strength deficits. Several different methodological approaches have been proposed for assessing lower limb muscle functional (Augustsson, et al., 2004; Claiborne, et al., 2006; Neeter, et al., 2006; Souza & Powers, 2009a, 2009b). These methods include computer-based isolated single joint evaluations and more functionally integrated FPTs (Augustsson, et al., 2004; Claiborne, et al., 2006; Neeter, et al., 2006; Souza & Powers, 2009a, 2009b) . Computer-based methods (e.g., HHD, PFD, and isokinetic dynamometry) have been reported as valid (Drouin, et al., 2004; Patterson & Spivey, 1992; Seger, et al., 1988; Tunstall, et al., 2005; Westblad, et al., 1996) and reliable (Aydog, et al., 2004; Eng, et al., 2002; Kollock, et al., 2010; Scott, et al., 2004; Symons, et al., 2005) means for assessing strength at the lower limb. However, much of this literature has focused on maximum strength with minimal attention given to others parameters of strength such as rapid force production (i.e. rate of force development) and strength endurance (Castro-Piñero, et al., 2010; Mebes, et al., 2008). In activities requiring rapid force production and the ability to sustain strength for time periods approximately 30 s in duration these measures may be of greater importance than maximum strength. In addition, while isolated computer-based measures are valid (Drouin, et al., 2004; Patterson & Spivey, 1992; Seger, et al., 1988; Tunstall, et al., 2005; Westblad, et al., 1996) and reliable (Aydog, et al., 2004; Eng, et al., 2002; Kollock, et al., 2010; Scott, et al., 2004; Symons, et al., 2005) for evaluating maximum strength one limitation is the lack of functionality of the movement pattern and fixed velocity testing set-ups (Andrade, et al., 2002). To help provide a more realistic representation of forces experienced during activities of daily living and sports or athletic participation, clinicians have incorporated functional performance tests, such as single limb hopping tasks (Clark, 2001). Logistically, the use of FPT may represent a more time efficient and cost method of assessing muscle function versus isokinetic instrumentation. Some FPTs have been reported within the literature as reliable and valid predictors of lower limb strength and power (Hamilton, et al., 2008). Research findings within the literature point to strong to very strong relationships between certain FPTs and isokinetic testing at the knee extensors and flexors (Bjorklund, et al., 2006; Hamilton, et al., 2008; Kovaleski, et al., 2001). Similar findings have been reported both in healthy and in ACL reconstruction participants (Hopper, et al., 2008; Keays, et al., 2003).

CHAPTER III

Experiment I: Assessing Hip Strength: A Comparison of Isometric Portable Fixed Dynamometry to Isokinetic Dynamometry at 1.05 rad·s^{-1} [60°·s^{-1}]

Title: Assessing Hip Strength: A Comparison of Isometric Portable Fixed Dynamometry to Isokinetic Dynamometry at 1.05 rad·s^{-1} [60°·s^{-1}]

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CHAPTER III

Experiment I: Assessing Hip Strength: A Comparison of Isometric Portable Fixed Dynamometry to Isokinetic Dynamometry at 1.05 rad·s^{-1} [60°·s^{-1}]

Proximal lower limb muscular strength may be a potential lower extremity injury risk factor (Fredericson, et al., 2000; Souza & Powers, 2009b; Tyler, et al., 2001). Researchers have theorized that the dynamic stabilizers found at the trunk and hip help to prevent aberrant movement mechanics at the lower limb during physical activities such as running (Hollman, 2006; Jacobs, et al., 2007; Leetun, et al., 2004; Powers, 2003; Souza & Powers, 2009a, 2009b) and landing from a jump (Boden, et al., 2000; Jacobs, et al., 2007). It is believed that the proximal musculature works synergistically to provide stability at the frontal and transverse planes helping to prevent excessive hip adduction and femoral internal rotation during these types of weight-bearing activities (Bolgla, et al., 2008; Hollman, 2006). In a study conducted by Claiborne et al. (2006) it was reported that concentric abduction strength displayed a significantly ($p< 0.05$) moderate correlation ($r = -0.37$) with frontal plane knee motion during a single leg squat task.

Decreased proximal strength has also been reported in symptomatic populations (Dierks, et al., 2008). During prolonged running Dierks et al. (2008) reported a significantly ($p < 0.05$) strong negative correlation ($r = -0.74$) between hip abduction strength and hip adduction angles with prolonged running in participants with patellofemoral pain syndrome. However, it is unclear if the observed weakness was a cause or result of the particular pathology.

These findings have prompted researchers and clinicians to begin evaluation of the current models within sports medicine for determining physical readiness prior to sports participation and returning to play following a lower limb injury (Best & Brolinson, 2005; Bradford & Lyons, 1991; Hamilton, et al., 2008; Wingfield, et al., 2004). Many have proposed the inclusion of computer-based strength evaluations into traditional pre-participation physical examinations (PPE) (Nadler, Malanga, et al., 2000; Scott, et al., 2004; Tyler, et al., 2001) and post injury return-to-play criterion (Augustsson, et al., 2004; Best & Brolinson, 2005; Hopper, et al., 2008; Neeter, et al., 2006). Practitioners currently use computer-based strength evaluations in the form of isokinetic dynamometry to help determine an athlete's return-to-play status following ACL reconstruction.

Isokinetic dynamometry evaluates muscular strength by restricting the speed at which a segment can move about a joint to a constant velocity (Brown, 2000; Deighan, 2003; Hill, 1996; Purkayastha, et al., 2006; Schmitz & Westwood, 2001). This theoretically allows for maximal muscle loading and mechanical output throughout the entire range of motion (ROM) at a selected joint (Deighan, 2003; Hill, 1996; Schmitz & Westwood, 2001). The testing velocity can be augmented by the clinicians prior to the start of the assessments. The selection of test velocity and number of repetitions performed are normally dependent on the goal of the evaluation (e.g., maximum strength versus power or endurance testing) (Brown, 2000). According to well-known force-velocity relationship an individual theoretically can obtain their maximum strength output (i.e. peak force) at lower movement velocities with that potential decreasing as the velocity of the movement increases (Hill, 1938). This relationship has been confirmed throughout the literature (Hill, 1996; Knapik & Ramos, 1980; Lord, Aitkens, McCrory, & Bernauer, 1992; Scudder, 1980; Stam & Binkhorst, 1992; Yoon, Park, Kang, Chun, & Shin, 1991).

Although many clinicians consider isokinetic dynamometry as the gold standard of strength assessments (Martin, et al., 2006), its cost (approximately $50,000-$60,000), lack of portability, and accessibility to clinicians (e.g. clinicians at high school, smaller college or clinical settings) limits its use to larger entities leaving smaller clinics to refer out to the larger outpatient clinics or hospital physical rehabilitation facilities. Researchers have reported that other less sophisticated types of dynamometry that are portable and more cost effective such as portable fixed dynamometry (PFD) are reliable means of assessing muscular strength (Kollock, et al., 2010; Nadler, DePrince, et al., 2000; Scott, et al., 2004). PFD is a hybrid version of the traditional load cell (e.g., hand-held dynamometer) or strain gauge that is attached via straps or mounted to a fixed structure (e.g. wall or column) (Kollock, et al., 2010).

Researchers have reported that PFD is a reliable method for assessing muscular strength; however its relationship to isokinetic maximum strength, specifically at the musculature of the hip has received minimal attention. Previous research investigating the association between isometric and isokinetic dynamometric strength protocols has focused on the knee flexors and extensors (Hill, 1996; Jameson, et al., 1997; Knapik, et al., 1983b) with scientists reporting very strong correlation coefficients ($r > 0.70$) (Hill, 1996; Jameson, et al., 1997;

Knapik, et al., 1983b). Investigations that have compared isometric test values to two or more isokinetic velocities have reported that isometric values demonstrated their highest association to the lower velocities with the strength of the association decreasing as the velocity of the isokinetic testing protocol increased (Hill, 1996; Knapik & Ramos, 1980; Lord, et al., 1992; Stam & Binkhorst, 1992).

It is unclear however if seated and standing hip isometric and isokinetic strength protocols will display this same relationship. Therefore, the purpose of this experiment will be to investigate the relationship between hip isometric and isokinetic concentric maximum strength performed at 60°/s. We hypothesize there will be a strong positive correlation between isometric and isokinetic absolute and normalized peak torque assessed at 60°/s. The isokinetic velocity of 60°/s was chosen based on the force-velocity relationship and earlier reported research that indicated a greater potential for creating maximum concentric force at the lower velocities (Hill, 1938; Hill, 1996; Knapik & Ramos, 1980). Thus, the isokinetic velocity of 60°/s represented a velocity in which maximum strength potential was increased, while still allowing for a dynamic and more functional strength testing protocol.

Methods

Study Design

This correlational study consisted of two-test sessions. The first session consisted of an isokinetic maximum strength test at 60°/s for the hip abductor (AB), hip adductor (AD), hip flexors (HF), hip extensors (HE), hip internal rotators

(IR), and hip external rotators (ER). The second session consisted of isometric assessments of the hip AB, AD, HF, HE, IR, and ER. The aforementioned lower extremity muscle groups were assessed in counterbalanced order. The main outcome measures included absolute peak torque (PT) and normalized PT represented as percentage of torque (%T).

Participants

Eighteen physically active males (N=9) and females (N=9) (22.33 ± 3.01 years, 173.00 ± 10.49 cm, 73.77 ± 16.69 kg) participated in the study. All participants were recreational athletes engaged in moderate activity, such as tennis, biking, jogging, etc, 2-3 times a week for at least 30 minutes. Participants had to be18 years of age and not have any lower extremity injury to the hip, knee, or ankle within the past 6 months. Additionally, participants with a history of lower extremity surgery to the hip, knee or ankle within the past 2 years were excluded. Prior to testing all participants were asked not to perform a rigorous lower extremity workout at least 24 hours prior to testing. The dominant limb, which was determined by asking the subject which leg they would use to kick a ball as hard as possible, was used for all testing (Kollock, et al., 2010; Krause, et al., 2007). All participants read and signed an approved institutional review board informed consent document prior to participation.

Instrumentation

Primus Rehabilitation System (RS) Dynamometer. The Primus RS (BTE Technologies, Hanover, MD) is a tri-mode dynamometer capable of isometric, isotonic, and isokinetic mode muscular testing. The Primus RS has a minimum and maximum isokinetic velocity of 5°/s and 240°/s. The Primus RS was used to evaluate isokinetic peak torque at 60°/s. The researchers calibrated the device according to the manufacturer's specifications. Our laboratory single session intra-rater intra-class correlation coefficients ($ICC_{3,1}$) were as follows: HF (0.66), HE (0.92), AB (0.90), AD (0.90), ER (0.88), and IR (0.78).

Evaluator Portable Evaluation System. The Evaluator (BTE Technologies, Baltimore, MD) and accompanying hardware was used to assess isometric measurements, specifically using a load cell designed to measure both compression and tensile forces. For all measures, the mechanical augmentation of the device allowed tensile force to be measured by enabling opposing forces to be clipped to the load cell. One end of the load cell was attached to an adjustable quick draw, tested at 25 kN, which was attached to a wall. The opposite end of the load cell was attached to an ankle strap proximal to the medial malleolus of the dominant leg (figure 3.1). The load cell was interfaced to a laptop computer via a data acquisition module. The load cell was calibrated within 2% of an 11.6 kg [25.5 lbs] certified weight daily as per manufacturer's specifications to ensure reliability across sessions. Laboratory reliability for lower extremity measures was established and reported in previous literature (Kollock, et al., 2010). The intra-rater $ICC_{3,1}$ values were as follows: HF (0.70), HE (0.77), AB (0.86), AD (0.90), ER (0.77), and IR (0.88), with a standard error of measure (SEM) ranging from 1.42 to 5.33 N (Kollock, et al., 2010). The intra-session ICC

$_{3,1}$ values for HF, HE, AB, AD, ER, IR ranged from 0.85 to 0.99, with a SEM ranging from 0.08 to 3.88 N. (Kollock, et al., 2010)

Testing Procedures

Subjects reported to the Sports Medicine Research Laboratory for two testing sessions. For session one, the participants reported to the Sports Research Laboratory in athletic attire. Anthropometric measures were obtained, and the subjects were instructed to perform a 10-minute warm-up on an exercise bike. Following the 10-minute warm-up isokinetic testing at 60°/s was performed. For the isokinetic testing, the researcher(s) instructed the subject to move the hip to the end range of motion in the direction opposite the concentric movement. The researcher(s) then moved the subject's limb back five degrees and used this point as the starting position. The researcher(s) then instructed the participant to move the hip in the direction of the concentric movement until the participant achieved end range. Again, the researcher(s) deducted 5 degrees from the final range. For all standing measures, the participant was allowed to hold onto the work head of the Primus RS during testing (figure 3.2). Prior to the actual test trials, the participant performed three practice trials at 30°/s. The researcher(s) instructed the participants to perform three maximum effort trials in a continuous manner at 60°/s. The investigator(s) evaluated the muscle groups in a counter balanced order. The researchers(s) recorded the highest force produced as the peak torque. A one-minute rest period was provided between each hip motion.

For session two, the participants reported to the Sports Medicine Research Laboratory in athletic attire for testing. The participants performed a

10-minute warm-up on an exercise bike. For the isometric peak torque, the participants performed 3 test trials of 5 seconds(s) in duration with a 15 s rest period between each trial. The investigator(s) evaluated the muscle groups of the lower limb in a counter balanced order. A one-minute rest period was provided between each hip assessment. The highest value produced was recorded as the peak torque.

Primus RS Isokinetic HE and HF Positioning Parameters. For the HE and HF the participants were positioned with the greater trochanter of the dominant limb lined up with the axis of rotation (figure 3.3). The participant was allowed to stabilize him or herself by holding onto the work head of Primus RS for stabilization. A foam pad was secured to the anterior aspect of the thigh (when measuring HF) or the posterior aspect (when measuring HE), with the bottom of the pad five centimeters above the superior pole of the patella. The thigh was placed in a position perpendicular to the floor (neutral position).

Primus RS Isokinetic AB and AD Positioning Parameters. For the AB and AD, the participant was positioned with the anterior aspect of the body facing the dynamometer work head. For the assessment of AB and AD, the axis of rotation was the point of bisection of a vertical line (at the aspect of the anterior superior iliac spine) and a horizontal line (at the aspect of the greater trochanter). A foam pad was secured to either the lateral (when measuring AB) or medial (when measuring AD) aspect of the thigh, with the bottom of the pad five centimeters above the superior pole of the patella. The thigh was placed in a position perpendicular to the floor (neutral position). The participant was allowed to hold on to the work head of the Primus RS during testing (figure 3.2).

Primus RS Isokinetic ER and IR Positioning Parameters. For the ER and IR, the participants were positioned in an upright-seated position with the hip and knee joints at 90° of flexion. The participant was positioned so that the center of the patella and shaft of the femur were in line with the axis of rotation of the dynamometer work head. A foam pad attached to a tool connected to the dynamometer work head was positioned above either the lateral malleolus (when measuring IR) or the medial malleolus (when measuring ER). Additionally, the subject had their dominant limb and torso strapped to the patient positioning chair to minimize any accessory motion during the evaluation (figure 3.4).

Evaluator PFD HE, HF, AB, and AD Positioning Parameters. Participants were tested in a standing position with the feet shoulder-width apart and with the load cell attached to the appropriate anatomical aspect (i.e. anterior, posterior, lateral, or medial) of the lower leg proximal to the medial malleolus via an ankle cinch strap. The researcher(s) instructed the participant to push or pull in the direction opposite the attachment of the load cell (figure 3.1). The participant was allowed to hold on to an adjustable handicapped walker during testing to help provide stability.

Evaluator PFD ER and IR Positioning Parameters. The participants were placed in an upright-seated position using the Primus RS' utility chair. The hip and knee of the test extremity was positioned in 90° of flexion so that the tibia of the test extremity was perpendicular to the floor. The load cell was attached to the appropriate anatomical aspect (i.e. lateral or medial) of the lower leg proximal to the medial malleolus via an ankle cinch strap. The researcher(s) instructed the participant to push or pull in the direction opposite the attachment of the load cell. The subject had their dominant limb and torso strapped to the patient positioning chair to minimize any accessory motion during the evaluation.

Data Reduction and Normalization

Force was recorded in pounds and later converted to Newtons (N). Peak torque was calculated through equation (1): torque = moment arm [meters] x force [N]. The moment arm was defined as the distance from the joint axis of rotation to the site of force application in meters [m]. All peak torque measures were normalized as a percentage of weight and height using the following equations:

Normalized PT = (PT [Nm]/ (weight [N] x height [m])) x 100..Equation (3.1)

(Bolgla, et al., 2008; Boling, Padua, & Alexander Creighton, 2009; Krause, et al., 2007). Normalized peak torque (relative to body size) values were used as a means of addressing the assumption that strength of the association between modes was simply reflective of differences in the body size between subjects (Andersen & Aagaard, 2006).

Statistical Analysis

Separate Pearson product moment bivariate correlations were used to evaluate peak torque and normalized peak torque between modes of muscular contraction. The correlation coefficients were interpreted using the scale set forth by Hopkins (Hopkins, 2002): trivial (0.0), small (0.1), moderate (0.3), strong (0.5), very strong (0.7), nearly perfect (0.9), and perfect (1.0). The alpha level was set *a priori* at .05. All coefficient correlations (*r* -values) were squared to calculate the coefficient of determination (r^2) in order to evaluate the percent of common variance between any two variables. The estimated power of this study was .71. Power analysis was performed post hoc using G*Power version 3.1.3 (Heinrich-Heine-Universität Düsseldorf, Germany).

Results

All means and standard deviations for the isometric and isokinetic absolute and normalized peak torque values have been described in table 3.1. All assumptions were met for all variables except HE, HF, AD absolute PT assessed with the PFD and AB normalized isokinetic PT. These analyses were re-run without the outliers (which was the same subject for 3 of the 4 outliers) which decreased the sample population for each analysis (n = 17). However, the correlation coefficients frame of reference (e.g., small, moderate, strong, etc) remained unchanged. PFD continued to demonstrate very strong association (r = .73 - .77) to isokinetic instrumentation for absolute HE, HF, and AD, while PFD continued to demonstrate a strong association (r = .60) to isokinetic instrumentation for the measure of normalized AB PT. Therefore, the decision was made to present our findings with the outliers included in the analysis.

Absolute peak torque correlation coefficients were reported in table 3.2. The correlation coefficients values between isometric PFD and isokinetic peak torque were statistically significant and ranged from strong ($r = 0.60$, $p \leq 0.05$) to very strong ($r = 0.87$, $p \leq 0.001$). Normalized peak torque correlation coefficients were reported in table 3.2.The correlation coefficient values for the relationship between normalized isometric PFD and isokinetic peak torque ranged from small ($r = 0.24$) to strong ($r = 0.68$). Normalized HF ($r=.52$, $p \leq 0.05$), AD ($r=.68$, $p \leq 0.01$), AB ($r=.50$, $p \leq 0.05$), ER ($r=.68$, $p \leq 0.01$) were all statistically significant. No other normalized values were statistically significant.

Discussion

The purpose of this experiment was to investigate the relationship between hip isometric and isokinetic maximum strength performed at 60°/s. The most important finding of this study was that the absolute peak torque measures demonstrated a strong to very strong positive correlation between isometric and isokinetic hip strength. This same relationship was not observed for normalized peak torque measures between the two modes, which demonstrated a small to large association. We believe this reduction in relationship strength after normalizing the data is a result of controlling for weight and height of the individual study participants (Andersen & Aagaard, 2006). In general, our correlation coefficients observed at the hip musculature were moderate to very strong, with the exception of normalized IR ($r = 0.24$). Thus, our hypothesis was support. While there is to the authors' knowledge no previous literature reporting information into the relationship of isometric to isokinetic testing at 60°/s at the hip musculature our findings appear to be similar to those reported at other muscle groups and different isokinetic test velocities (Hill, 1996; Jameson, et al., 1997; Knapik, et al., 1983b). This is an important finding given the growing use of portable isometric devices for assessing the strength of the musculature of the hip (Dierks, et al., 2008; Fredericson, et al., 2000; Jacobs, et al., 2007), due to their minimal cost and ease of test administration (Bohannon, 1990; Scott, et al., 2004). Our study is one of the few to compare isometric measures collected via PFD to isokinetic evaluations. Knapik et al. (1983b), using sophisticated dynamometry for both isometric and isokinetic assessments at 36, 108, and 180°/s, reported *r*-values ranging from 0.71- 0.83 for knee extensor and 0.49-0.80 for knee flexor strength, with the correlation being the strongest at the lower velocities. Hill et al. (1996) using hand-held and isokinetic dynamometry at 60°/s reported very strong correlations ($r = 0.77$ to 0.82) for knee flexion and extension.

Although our observed correlation coefficients are comparable to those reported by Hill et al. (1996) and Knapik et al. (1983b), the use of PFD may be more advantageous than unmodified hand-held or isokinetic dynamometry. In contrast to hand-held dynamometry that requires clinicians to produce high forces to counter the force exerted by the patient, PFD negates the patient-tester force-counterforce interaction (Bohannon, 1997a; Martin, et al., 2006; Nadler, DePrince, et al., 2000). This interaction could be problematic when evaluating the larger muscle groups of athletes such as the quadriceps femoris (Martin, et al., 2006), resulting in a great deal of variability between trials (i.e. coefficient variation) due to an inability to stabilize the segment about the joint being tested

(Bohannon, 1997a; Martin, et al., 2006; Nadler, DePrince, et al., 2000). In terms of isometric PFD and isokinetic testing, these two methods vary considerably in their cost, portability, and approach to assessing muscular strength. The cost and lack of portability of isokinetic instrumentation presents difficulty with implementation in all settings and scenarios such as high school large-scale PPEs. Another contrasting difference between these two methods is that they represent varied methodological approaches with different set-up protocols and movement velocities. Although, these methods differ in movement velocity, we hypothesize that the proximity of the two test velocities (zero and 60°/s) allowed for our findings and suggest that perhaps PFD might be a suitable substitution for isokinetic testing at 60°/s. This is evidenced in our observation of strong to very strong relationships in 10 of the 12 relationships assessed with normalized HE displaying a moderate relationship ($r = 0.42$) between modes. This hypothesis is based on the findings of earlier reported studies (Hill, 1996; Jameson, et al., 1997; Knapik, et al., 1983b), which coincides with conventional biomechanical principles such as the torque-velocity relationship proposed by Hill (1938). The torque-velocity relationship holds that as concentric velocity increases, torque decreases. According to Hill et al. (1996), the torque-velocity curve relates to the peak torque that a muscle(s) can exert during a given movement with respect to the velocity of that movement. Furthermore, the maximum concentric torque occurs at a point in which the velocity nears zero (i.e. isometric condition) (Hill, 1996). Likewise, torque decreases as the velocity increases forming a curvilinear path (Hill, 1996). Thus, a larger degree of association between modes is to be expected the more closely the test velocities approximate.

Since this relationship did not hold true for the normalized IR measures between PFD and isokinetic, we surmise that although both methods measure a similar phenomenon (i.e. strength), the dynamic patterns of the isokinetic evaluation require that the participant produce force in a shorter time (Stam & Binkhorst, 1992). Dynamic contraction produced by isokinetic instrumentation may also necessitate a rapid initial limb movement at the start of repetition, particularly at higher velocities (Stam & Binkhorst, 1992). This is only speculative, since we did not record the time taken to perform an isokinetic repetition. We do however hypothesize that the isokinetic IR motion may have represented a much more unfamiliar movement pattern versus the other isokinetic movements. Thus, perhaps reflex actions and patterns of coordination play a greater role in the performance of isokinetic evaluations even when performed at slower velocities (Stam & Binkhorst, 1992), with unfamiliar or unnatural motions resulting in reduced values for one muscle group versus the other. This may suggest a need for an isokinetic familiarization session prior to evaluations in future studies. This is a limitation of the present experiment. The present study did not provide a period of familiarization at the test velocity of 60°/s. This may in fact account for some of the lack of common variance noted between the methods, which displayed a very wide range (17 – 75% common variance). Other limitations of the present study include the following. First, since participants were not randomly sampled the findings of the experiment may not be generalizable and limited to this sample, which was a sample of convenience. Second, although all participants were recreational athletes, varied athletic participation and years of experience may have influenced their performance on the computer-based strength testing. This may have also in some part contributed the excessive variability observed within our strength values. It is plausible that a more homogenous sample of recreational athletes (i.e. those with similar sport or athletic backgrounds) would have demonstrated less variability. Finally, due to the construct of the two devices the use of similar lever arm length for AB, AD, HE, and HF measures were not possible. The moment arm for the PFD were taken from the greater trochanter to the lateral malleolus, while the moment arm length was the distance from the greater trochanter to a point five centimeters above the superior pole of the patella. The more distal point of force application used with the PFD set-up protocol may have led to a greater activation of the quadriceps (HF) and hamstrings (HE) subsequently inflating the measures. However, this could not be the case for the hip AB and AD values. The point of force application used for the PFD AD and AB measures are considerable more distal than the point of force application used for the AD and AB measures of the isokinetic protocol, which theoretically would have place these two muscle groups at a disadvantage when compared to the measurement taken with the isokinetic protocol. More over the use of normalized strength measures would act to mitigate some of the inflation due to these differences in moment arm length. Future studies should seek to address some of these aforementioned limitations.

Clinical Relevance

Clinically, our findings suggest that although it may be ideal to measure strength through sophisticated dynamic means (e.g., isokinetic instrumentation), the use of PFD may be a viable option for determining absolute strength at select muscle groups of the hip (e.g., HE, HF, AD, AB, and ER) during traditional pre-participation physical examinations (PPE) and post injury return-to-play criterion. Based on our findings it appears that isometric absolute PT may be a strong indicator of isokinetic testing at 60°/s for the musculature at the hip. This is an important clinical finding given the wide spread use of portable isometric devices because of their simplicity, portability, objectivity, and reliability (Kollock, et al., 2010; Li, et al., 2006; Taylor, et al., 2004; Wang, et al., 2006). However, caution is warranted. First, the present investigation was powered (estimated .70) to evaluate the association between isometric strength and isokinetic testing at 60°/s via separate Pearson product-moment correlations, thus our findings only give insight into the associations between these two modes and not into cause and effect relationships (Requena, et al., 2009). Second, following normalization relative to height and weight a noticeable decrease in common variance was observed with all of the muscle groups evaluated, perhaps indicating that body size (i.e. height and weight) acts as a confounder distorting the relationship between isometric and isokinetic testing at 60°/s (Portney & Watkins, 2000). This also (along with the earlier mentioned varied athletic participation and years of experience) may have been a contributor to the excessive between subject variability observed within our absolute strength values.

Conclusion

The association between isometric PFD and isokinetic at 60°/s absolute peak torque displayed strong to very strong correlations coefficients, while normalized peak torque relationships were generally moderate to strong. The results of this study indicate a potential may exist for substituting isometric PFD for isokinetic testing at 60°/s when evaluating the musculature of the hip. However, further investigation is needed into these relationships to validate the use as a predictor of isokinetic strength evaluated at 60°/s.

CHAPTER IV

Experiment II: Maximum Strength and its use as an Indicator of Rapid Force Production and Endurance Strength

Title: Maximum Strength and its use as an Indicator of Rapid Force Production and Endurance Strength

Authors: Roger Kollock, Bonnie Van Lunen, Stacie Ringleb, James Oñate

CHAPTER IV

Experiment II: Maximum Strength and its use as an Indicator of Rapid Force Production and Endurance Strength

Proximal lower extremity muscular strength (i.e. hip and thigh strength) may play a vital role in athletic performance and the susceptibility to injury (Fredericson, et al., 2000; Souza & Powers, 2009b; Tyler, et al., 2001). Strength deficits in the lower extremity region in concert with other associated risk factors may increase an individual's susceptibility to injuries such as noncontact anterior cruciate ligament ruptures (Claiborne, et al., 2006; Kollock, et al., 2008), patellofemoral pain syndrome (Niemuth, et al., 2005; Souza & Powers, 2009a, 2009b; Tyler, Nicholas, et al., 2006), and strains of the groin (Tyler, et al., 2001) or hamstring musculature (Croisier, et al., 2008). This has prompted many to propose the inclusion of lower limb strength-testing batteries into conventional preparticipation physical evaluations (PPE) (Nadler, Malanga, et al., 2000; Scott, et al., 2004; Tyler, et al., 2001) and return-to-play (RTP) criterion (Augustsson, et al., 2004; Best & Brolinson, 2005; Hopper, et al., 2008; Neeter, et al., 2006) in order to better identify athletes with asymmetries and agonist-antagonist strength ratio deficits.

In the clinical setting, muscular strength is defined as the ability of a muscle(s) to produce force through active tension (Hislop & Perrine, 1967). Although the force produced by a muscle group during periods of active tension occurs in a linear manner, the motion at a joint is generally rotary, moving an object about an axis (Hogrel, et al., 2007). Therefore, when assessing intact joint actions (i.e. in vivo), strength is best quantified in terms of torque (Hogrel, et al., 2007). Depending on the goals or constraints of the task performed, the torque (i.e. strength) generated through the active tension of a muscle group during an isolated joint movement results in movement or stabilization of the segment(s) about that joint (Fukunaga, et al., 1997).

As it pertains to the field of sports medicine, strength has most commonly been evaluated through maximum strength testing, (Mirkov, et al., 2004; Sale, 1991) which is the highest level of voluntary torque produced by a muscle around an axis under isometric, eccentric, and concentric conditions (Mebes, et al., 2008). However, Mebes et al. (2008) notes that with exercise physiology, it is important to keep in mind that muscle strength, as a sensorimotor skill, has to be differentiated into separate aspects or parameters: maximum strength, rate of torque development (RTD), and strength endurance (Castro-Piñero, et al., 2010; Mebes, et al., 2008). Although each parameter evaluates a similar phenomenon (i.e. muscular strength), each targets a uniquely different function (or ability) of the muscle group over uniquely different intervals of time (Aagaard, et al., 2002; Andersen & Aagaard, 2006; Mebes, et al., 2008).

Maximum strength, also termed peak torque, is typically evaluated over a 3-5 second period. Strength data obtained from elbow flexor and knee extensor tests indicate that generation of maximum muscular strength typically occurs at time-periods greater than 300 ms (Aagaard, et al., 2002; Andersen & Aagaard, 2006; Thorstensson, Karlsson, Viitasalo, Luhtanen, & Komi, 1976). This is perhaps problematic considering the increase in reports about the potential functional importance of rapid neuromuscular activation in the first 50 ms, following initial ground contact during an injury situation (Koga et al., 2010; Krosshaug et al., 2007). In a report by Krosshaug, et al. (2007) which evaluated 39 videos of anterior cruciate ligament injury situations, it was revealed that the timing of noncontact ACL injury ranged between 17 to 50 milliseconds after initial ground contact. This brief time period perhaps leaves minimal time for mechanosensory feedback mechanisms to prevent injury (Zebis, Andersen, Bencke, Kjaer, & Aagaard, 2009). Arguably, in a scenario such as this, a greater emphasis is on the muscles ability to generate torque about a joint rapidly. This ability to generate torque rapidly is termed RTD and is the rate of rise in joint moment at the onset of a muscle contraction (Aagaard, et al., 2002), expressed as the Δtorque/Δtime (Aagaard, et al., 2002; Andersen & Aagaard, 2006). RTD is considered an important parameter in evaluating the quick responding qualities of the neuromuscular system (Aagaard, et al., 2002; Gruber & Gollhofer, 2004; Hakkinen & Komi, 1983; Hakkinen, Komi, & Alen, 1985; Schmidtbleicher & Haralambie, 1981) with high levels of RTD considered a prerequisite for tasks that require fast limb movements or allow a limited time for muscular action (Gruber & Gollhofer, 2004). In addition, RTD plays a key role in the development of maximal muscle power (force · velocity) (Stone et al., 2004). During task performance, RTD determines the magnitude of the acceleration in the initial phase of a segment's movement, ultimately influencing the velocity of the segment's movement (Aagaard, et al., 2002; Kraemer & Newton, 2000) and consequently the power produced during that movement. Although high RTD is a critical attribute that leads to high power output, it is important to remember that these two components (i.e. RTD and power) are not interchangeable (Willardson, 2010). In terms of strength, high RTD is arguably desirable during fast and or short-lasting movements (especially in situations with limited joint excursion) (Caserotti, Aagaard, Buttrup Larsen, & Puggaard, 2008) such as sudden cutting and pivoting while running.

However, in sports and other strenuous activities, the ability to produce adequate levels of strength and to sustain it (i.e. strength endurance) may be equally important to performance and the susceptibility of injury or re-injury. Strength endurance is a muscle or muscle groups' ability to resist fatigue under anaerobic strength conditions and is based on anaerobic capacity (Mebes, et al., 2008). There is some literature implicating central fatigue mechanisms to aberrant lower movement mechanics during athletic or sports-type maneuvers (e.g. single leg landing tasks) (Kernozek, Torry, & Iwasaki, 2008; McLean & Samorezov, 2009), minimal information exists in peripheral fatigue and its effects on movement mechanics. An investigation by Hawkins, et al. (2001) reveal a greater frequency of injuries during the final 15 minutes of the first half and the final 30 minutes of the second half of a professional English league football (i.e. soccer) match. Perhaps during these later stages of competition the effect of neuromuscular fatigue diminishes or alters the muscles ability to generate force, resulting in a retardation of the neuromuscular response or control mechanisms. This phenomenon may lend itself to reduced postural control and functional joint stability potentially increasing the risk to injury during athletic performance.

To date, under isolated single joint isometric conditions, there have been no studies investigating the relationship between all three parameters (i.e. maximum strength, RTD, and strength endurance), thus raising the question of the potential necessity of evaluating all three, especially if maximum strength is a strong indicator of both RTD and strength endurance of the proximal lower limb musculature. Clinicians can easily conduct maximum strength testing through hand-held (HHD) and portable fixed dynamometry (PFD); however, RTD and measures of strength endurance require the inclusion of more sophisticated instrumentation (e.g. data acquisition modules) and signal analysis and processing software such as LabView (National Instruments Corporation, Austin, TX) or Matlab (The MathWorks Inc., Natick, MA). The additional resources (e.g., money, time, personnel) needed to collect RTD and strength endurance may not be an absorbable cost and justifiable use of a clinician's valuable time.

Although there is limited research investigating the association of the three aspects together, literature does exist comparing maximum strength to both RTD and strength endurance. It has been reported that maximum strength assessed at the knee extensors accounts for approximately 80% of the total variance in rate of force development during later phase (150-250 ms) of the muscle contraction (Andersen & Aagaard, 2006). In regards to the relationship between maximum strength and strength endurance, Surraka, et al. (2004) reported finding a significant moderate correlation between the two variables when assessed at the knee flexors of patients with multiple sclerosis (MS), however the group did not find this same relationship for the knee extensors.

Given the lack of research comparing maximum strength, RTD, and strength endurance, their potential importance to lower limb injury risk and the proposed inclusion of lower extremity strength batteries into PPE and RTP scenarios, the goal of this study was to address the question of the potential necessity of evaluating all three parameters. If maximum strength is indicative of the other parameters, this information could help streamline strength-testing batteries, thus minimizing the time and cost of evaluations. Therefore, the purpose of this study was to investigate relationships between the three parameters of muscular strength. First, we hypothesized that there would be a significant positive correlation between maximum strength and RTD. Second, we hypothesized that maximum strength and RTD would display a significant positive correlation to strength endurance.

Methodology

Study Design

This correlational study consisted of the following advanced isometric assessments: maximum strength (peak torque), rate of torque development (RTD), and strength endurance for the hip abductor (AB), hip adductor (AD), hip flexors (HF), hip extensors (HE), hip internal rotators (IR), hip external rotators (ER), knee flexors (KF), and knee extensors (KE). The peak torque (PT) and RTD were collected simultaneously and prior to the assessments of strength endurance. The main outcome measures included absolute and normalized PT and RTD at four separate time intervals (0-30, 0-50, 0-100, and 0-200 milliseconds), and a fatigue index (FI) ratio score (i.e. measure of strength endurance) for each muscle group.

Participants

Sixty-two physically active recreationally athletic (mass 74.63±14.79 kg; height, 171.23 cm±10.72; age, 21.05±2.82), males (N=30) and females (N=32) were recruited. A recreational athlete was defined as an individual engaged in moderate activity, such as tennis, biking, jogging, weight lifting, etc, 2-3 times a week for at least 30 minutes. Individuals were excluded if they had any of the following conditions: 1) an ACL tear within the last two years 2) restricted within the last six months by an athletic trainer or team physician from participating in any practice or competition for longer than two days because of a lower extremity injury, or 3) a neurological disorder. Participants were asked not to perform a rigorous lower extremity workout at least 24 hours prior to testing. All measures were collected for the dominant limb which was determined by asking the subject which leg they would use to kick a soccer ball, using their maximal force effort. Participants read and signed a consent form that was approved by the institutional review board.

Instrumentation

Isometric Strength Assessment. Isometric strength data were collected using a commercial dynamometer (Model: LCR, OmegaDyne, Inc, Stamford, CT). The data were sampled at 1000 Hz (PT and RTD) and 100 Hz strength endurance using a 1 MHz, 24 bit USB Data Acquisition Module (Model: NI-DAQ 9237, National Instruments Corporation, Austin, TX) and logged using LabVIEW

Signal Express (National Instruments Corporation, Austin, TX) . The data acquisition module converted the voltage received from a load cell to strain (National Instruments Corporation Technical Support, personal communication, February 3, 2010). Strain was scaled to quantities of force in pounds [lbs] using a series of 38 known weights (loads) ranging from 5 to 213.2 lbs (22.5 to 959.4 N). Force in pounds [lbs] was later converted to Newtons [N]. All logged data were stored on a laptop computer for offline processing and analysis. The data were filtered post log using a digital fourth order butterworth filter with an optimal cutoff frequency developed within LabVIEW Signal Express. A power spectrum density (PSD) analysis was performed using a custom Matlab (The MathWorks Inc., Natick, MA) program to determine the optimum cut-off frequency of 50 Hz. The researcher(s) verified the load cell was within (1%) of a known weight (178 N) daily to ensure reliability.

Testing Procedures

Subjects reported to the Sports Medicine Research Laboratory in athletic attire for one testing session. Anthropometric measures (mass, height, shank length, and leg length) were obtained, and the subjects were instructed to perform a 10-minute warm-up on an exercise bike. For the isometric strength parameters of maximum strength (i.e. PT) and RTD, the participants performed 3 test trials, each 5 seconds(s) in duration, with a 60 s rest period between each trial. The muscle groups were evaluated in a counterbalanced order. Scripted instructions and prompts were used.

Following the PT and RTD strength analyses the subject was given a 10 minute rest period. Immediately following the rest period, subjects underwent isometric strength endurance testing, which evaluated the same muscle groups tested during the PT and RTD analyses. The strength endurance testing was performed in the same testing positions as the PT and RTD analyses. For the strength endurance testing subjects performed two isometric contractions, each for 30 s. Each 30 s contraction was separated by a two minute rest period. In order for a trial to be deemed valid, the subject had to reach a minimum of 95% of their maximal isometric PT (as determined by the previous PT analyses) within the initial five seconds of the start signal. If this criterion was not met within the initial five seconds the attempt was halted after the initial five seconds and the subject was allowed a two minute rest period. This minimum of 95% of PT requirement was adopted to ensure that the subjects were giving a maximal effort at the start of each contraction. As with the PT and RTD analyses the muscle groups were evaluated in a counterbalanced order and scripted instructions and prompts were used. The strength endurance scripted instructions and prompts were similar to the maximum strength and RTD script with the exception of asking the participants to "keep pulling" approximately every 5 sec until completion of the task.

Standing Isometric Hip Protocol. AB, AD, HE, and HF were assessed in a standing position. The participants stood with feet shoulder width apart with the load cell attached to the appropriate anatomical aspect (i.e. medial [AB], lateral [AD], anterior [HE], and posterior [HF]) of the lower leg proximally above the medial malleolus via an ankle cinch strap (figures 4.1 and 4.2) (Kollock, et al., 2010).

Seated Isometric Strength Protocol. KE, KF, ER, and IR were performed in an upright-seated position. The hip and knee of the test extremity were positioned in 90 °of knee flexion so that the tibia of the test extremity was perpendicular to the floor. The load cell was attached to the appropriate anatomical aspect (i.e. posterior [KE], anterior [KF], lateral [ER], and medial [IR]) of the lower leg proximal to the medial malleolus via an ankle cinch strap (figures 4.3 and 4.4) (Kollock, et al., 2010).

Data Reduction and Normalization

The isometric strength data were reduced in the following manner. Force [N] was then used to calculate torque [Nm] using equation 2.1: torque = moment arm [m] x force [N], where the moment arm is the distance between lateral malleolus and the joint axis of rotation. This distance was represented by the shank or leg length measures. The highest value of the three isometric attempts was used to determine the maximum strength (i.e. absolute peak torque [Nm]) and absolute RTD [Nms^{-1}]. The initial 200 milliseconds after the onset of the contraction were used to calculate the absolute RTD across four separate time-periods (0-30, 0-50, 0-100, and 0-200 ms) (Aagaard, et al., 2002; Christensen, et al., 2008) (figure 4.5). The point at which the torque is 7.5 Nm greater than the baseline value was defined as the onset of the muscle contraction (Aagaard, et al., 2002). Absolute PT and RTD were collected during the same test trial. The absolute strength measures represent the force data prior to normalizing the data relative to height and weight. Absolute peak torque [Nm] and RTD [Nms^{-1}] were both normalized relative to weight and height via the following equations:

Normalized PT = (PT [Nm]/(weight [N] x height [m])) x 100...Equation (3.1)

(Bolgla, et al., 2008; Boling, et al., 2009; Krause, et al., 2007).

Normalized RTD = (RTD [Nms^{-1}]/(weight [N] x height [m])) x 100...Equation (4.1).

Strength endurance was determined through a fatigue index (FI) ratio score:

FI = (1 – (AUTC / HAUTC)) x 100.................................Equation (4.2)

(Meldrum, et al., 2007; Sanjak, et al., 2001; Schwid, et al., 1999; Surakka, Romberg, Ruutiainen, Virtanen, et al., 2004), where FI is equal to 1 minus the quotient of the area under the force-time curve (AUFC) divided by the hypothetical area under the force-time curve (HAUFC). The AUTC is the integral of force for a 30-second trial time, while the HAUTC is the peak force value observed between 0-5 seconds of the 30-second trial time (figure 4.6). A lower fatigue index score indicates a greater resistance to fatigue.

Statistical Analysis

Separate Pearson product-moment correlations were used to evaluate the association between PT, RTD, and strength endurance. The alpha level was set *a priori* at $p \leq 0.05$. The Hopkins (Hopkins, 2002) scale was used to interpret all correlation coefficients: trivial (0.0), small (0.1), moderate (0.3), strong (0.5), very strong (0.7), nearly perfect (0.9), and perfect (1.0). All coefficient correlations (*r* - values) were squared to calculate the coefficient of determination (r^2) in order to evaluate the percent of common variance between any two variables.

Results

Absolute Strength

The means and standard deviations for the strength parameters are described in table 4.2. Tables 4.3 details the relationship found between absolute PT, RTD, and strength endurance. All measures of absolute PT demonstrated a significant nearly perfect positive correlation (r=. 975-.984, $p \leq 0.001$) to absolute RTD at the time intervals of 0-30, 0-50, 0-100, and 0-200 ms, explaining 95% to 96% of the variance. Absolute AB, HE, HF, KE, and IR PT demonstrated a trivial to small positive correlation (r=.024-.206) to strength endurance. Absolute AD PT displayed a moderate positive correlation (r=.304) to AD strength endurance, with Absolute KF and ER PT both demonstrating a significant moderate positive correlation with KF (r=.340, $p \leq 0.05$) and ER (r=.313, $p \leq 0.05$) strength endurance measures. Overall, absolute PT accounted for 0 – 11.5 % of the variance in the strength endurance measures.

A trivial to small positive correlation (r=.045- .215) was discovered for the association of AB, HE, HF, KE, IR strength endurance to RTD at 0-30, 0-50, 0-100, and 0-200 ms. A significant moderate positive correlation (r=.315-.333, $p \leq 0.05$) was found between AD strength endurance and AD RTD at 0-30, 0-50, 0-100, and 0-200 ms. ER strength endurance demonstrated a positive moderate correlation (*r*=.303-.306) with ER RTD at 0-30, 0-100, and 0-200 ms, while displaying a significant moderate positive correlation (*r*=.315, *p*≤0.05) to ER RTD at 0-50 ms. RTD explained 0% - 11% of the variance in the strength endurance measure.

Normalized Strength

Tables 4.4 details the relationship found between normalized PT, RTD, and strength endurance. A nearly perfect positive correlation (*r*=.917-.988, *p*≤0.001) was found between all measures of normalized PT and RTD at 0-30, 0-50, 0-100, and 0-200 ms, except for HF PT. Normalized HF PT demonstrated a significant very strong positive correlation with RTD at 0-50 (*r*=.881, *p*≤0.001) and 0-100 (*r*=.893, *p*≤0.001) ms and a significant nearly perfect positive correlation with RTD at 0-30 (r=.899, *p*≤0.001) and 0-200 (*r*=.897, *p*≤0.001) ms. Overall, normalized PT accounted for 77.6% - 97.6% of the variance in normalized RTD at separate time intervals. Normalized HE, KE, IR PT demonstrated a small positive correlation (*r*=.205-.232) with strength endurance, while normalized AB (*r*=.295) and HF(r=.301) PT showed a moderate positive correlation. A significant moderate positive correlation was revealed for the association between normalized PT and strength endurance at the ADs (*r*=.341, *p*≤0.05) and KFs (*r*=.460, *p*≤0.001). Normalized PT accounted for 4.2% - 21.1% of the variance strength endurance measures. In general, a significant moderate correlation was observed between normalized RTD and strength endurance at the AD, HF, KF, and ER, while a small correlation was observed between normalized RTD and strength endurance at the AB, HE, KE, and IR. Normalized RTD accounted for 4.2% - 20% of the variance in strength endurance.

Discussion

The main finding of this study was that although maximum strength was highly related to an individual's ability to develop force rapidly (i.e. RTD) it does not appear to be an indicator of muscular endurance. The results of this study partially support our hypotheses in that PT was highly correlated with RTD, yet demonstrated a poor correlation to strength endurance. Thus, our findings support the notion that assessing one aspect of strength (i.e., PT) can provide information relative to another aspect of strength (i.e., RTD), but not all parameters of strength (i.e., endurance).

Relationship between Maximum Muscle Strength and RTD

Prior investigations exploring the association between PT and RTD have revealed positive relationships between these two aspects of strength (Andersen & Aagaard, 2006; Mirkov, et al., 2004); therefore, we hypothesized this same finding. Our findings supported our hypothesis; however in contrast to Andersen et al. (2006) we additionally observed a nearly perfect relationship ($r \geq 0.90$, $p \leq 0.001$) between PT and initial phase RTD (0-30 and 0-50 ms). Andersen et al. (2006) reported finding correlation coefficients ranging from approximately .40 to .89, with the strength of the correlation increasing as the interval of time increased from 0-10 ms to 0-250 ms. Their findings suggested that PT was more indicative of late phase RTD (time periods > 90 ms), accounting for 52 – 81% of the variance. Earlier investigations have suggested that other physiological factors such as stiffness of the muscle-tendon complex (Bojsen-Moller, Magnusson, Rasmussen, Kjaer, & Aagaard, 2005), muscle fiber type (Bottinelli, Canepari, Pellegrino, & Reggiani, 1996; Stone, et al., 2004), and neural drive to the muscle (Aagaard, et al., 2002) play a greater role in early phase RTD (Andersen & Aagaard, 2006). Although our results displayed correlation coefficients ≥ .89 for the periods 0-100 and 0-200 ms (i.e. late phase), we did not observe a similar relationship at the early or initial phases of RTD (i.e. 0-30 and 0-50 ms) with our PT measures accounting for 78 to 97% of the variance. After correcting (i.e. normalizing) our strength measures relative to height and weight, in general, there was a minimal decrease in the strength of the associations between PT and RTD. PT and RTD were normalized relative to height and weight to avoid the opinion that the strength of the associations were merely reflective of differences in body size between the participants (Andersen & Aagaard, 2006). In addition, the strength of the relationship did not always increase as the interval of time increased as demonstrated in Andersen et al. (2006) However, KE did display a similar trend to that reported by the Andersen et al. (2006) Overall, our findings support that PT and RTD relationship is fairly similar across time points and the proximal lower extremity muscle groups.

We believe the disparity between Andersen, et al. (2006) and our study is reflective of the difference between sample populations. Andersen, et al. (2006) had a less active sample (25 healthy sedentary male students from the University of Copenhagen) while we examined recreationally active males and females.

Our recreationally active individuals were defined as those who engaged in moderate activity, such as tennis, soccer, basketball, biking, jogging, weight training, etc., 2-3 times a week for at least 30 minutes. Our findings, coupled with earlier literature (Aagaard, et al., 2002; Suetta et al., 2004), may indicate that recreationally active individual's, as compared to those with sedentary lifestyles, demonstrate a greater ability to generate force more rapidly during the initial phases (0-30 and 0-50 ms). Several studies have reported increases in early phase RTD following implementation of either strength (Aagaard, et al., 2002; Holtermann, Roeleveld, Vereijken, & Ettema, 2007; Suetta, et al., 2004) or sensorimotor (Gruber & Gollhofer, 2004) training programs. Aagaard and colleagues (Aagaard, et al., 2002) reported that RTD at KE displayed a 20% and 18% increase respectively for 0-30 and 0-50 ms time intervals following a 14-week progressive heavy resistance-training program. Using a 12-week strength-training program, Suetta et al. (2004) reported observing an increase of 45% and 31% at 0-30 ms and 0-50 ms, respectively in RTD at the KE. Finally, Gruber and Gollhofer (2004) reported a significant increase in leg press RFD at 0-30 (p=0.009) and 0-50 (p=0.034) following a four week sensorimotor training in which participations engaged in two 60 minute training session twice a week. This increase in RTD may be a result of an increase in motoneuron output (efferent neural drive) because of strength training (Aagaard, et al., 2002). Paralleled gains between the two (RTD and neural drive) after completion of a regimented strength program have been reported in prior literature (Aagaard, et al., 2002). This increase in neural drive may primarily reflect an increase in motoneuron firing frequency that in return influences RTD (Aagaard, et al., 2002). Arguably, sedentary or less-conditioned individuals may have a lower motoneuron output (efferent neural drive) potential at the initial phases when compared to individuals with recreationally active lifestyles resulting in a decreased ability to produce force rapidly within the first 50 ms after the onset of a contraction.

These differences may also be in some part related to differences in muscle morphology (e.g. muscle cross sectional area and fiber type composition) between sedentary and recreationally active individuals. Reports have indicated that muscle cross sectional area and fiber compositions are influencers to both maximum strength and RTD (Andersen & Aagaard, 2006; Close, 1972; Schantz, Randall-Fox, Hutchison, Tyden, & Astrand, 1983). It is plausible that recreationally active persons would be stronger (relative to height and weight) and possess a greater percentage or larger type II muscle fibers (Stone, et al., 2004). In short, recreationally active individuals may have an adaptive advantage over sedentary individuals in terms of early phase RTD due to their active lifestyles.

Relationship of Maximum Muscle Strength and RTD to Endurance Strength

In our second hypothesis, we proposed that maximum strength and RTD would display a positive correlation to strength endurance. Our findings partly supported this hypothesis as KF PT and AD, HF, and KF RTD did demonstrate a significant ($p \leq 0.05$) positive correlation to strength endurance. However, the relationship only accounted for 9% - .21% of the variance. Although our data represents an active healthy population the findings between PT and strength endurance are in line with those reported in symptomatic populations (Sanjak, et al., 2001; Surakka, Romberg, Ruutiainen, Virtanen, et al., 2004). Sanjak et al. (2001) reported finding that muscular weakness (i.e. PT) and endurance evaluated at the KE were poorly correlated ($r = 0.016$) in patients with amyotrophic lateral sclerosis, while Surakka et al. (2004) observed small to moderate correlation at the KE ($r = -0.23$ to -0.15) and KF ($r = 0.21$ to 0.43) in patients with multiple sclerosis. Taken together these findings arguably highlight the need to assess both maximum strength and endurance. The relationships between RTD and strength endurance were similar to those observed between PT and endurance, thus as with PT, RTD does not appear to be indicative of strength endurance either. The reason for this lack of strength in the relationship of PT and RTD to endurance is perhaps because fatigue does not occur due to the impairment of a single process; instead it is the results of numerous mechanisms (Enoka, 2002).

Fatigue is a result of the decrement of numerous sensory and motor mechanisms (Enoka, 2002). Arguably, during the performance of the strength endurance battery the activity requirements stressed a range of physiological processes (Brooks, 2000; Enoka, 2002; Enoka & Duchateau, 2008) such as primary motor cortex activation (Enoka, 2002), supraspinal drive to motoneurons (Bilcheck, et al., 1992; Enoka, 2002; Enoka & Duchateau, 2008; Westerblad & Allen, 2002), activation of the motor units and muscles (Enoka, 2002), neuromuscular propagation (Enoka, 2002), and muscle fiber excitation-contraction coupling (Bilcheck, et al., 1992; Enoka, 2002; Westerblad & Allen, 2002). Additionally, physiological processes such as metabolic substrate availability (e.g. glycogen) (Brooks, 2000; Enoka, 2002), intracellular milieu (Brooks, 2000; Enoka, 2002), contractile apparatus (Enoka, 2002), and blood flow to muscles (Enoka, 2002) potentially may have been impaired. We speculate that these aforementioned mechanisms perhaps played a greater role than PT and RTD in the sample populations' ability to produce near maximal levels of strength and to sustain it for prolonged periods.

Clinical Relevance

Clinically, our findings indicate that although strength is a multifaceted phenomenon with three specific aspects or parameters, it may not be necessary to measure both PT and RTD individually in the context of PPEs and RTPs evaluations. Based on our findings, it appears that PT is a strong indicator of RTD. In addition, we observed that this relationship is not only true for late phase RTD (0-100 ms and 0-200 ms), as reported in previous literature (Andersen & Aagaard, 2006), but also in the initial phases of RTD (0-30 ms and 0-50 ms) in recreationally active individuals. This is an important clinical finding considering the data presented by Koga, et al. (2010) who proposed relatively short time windows between initial contact and ACL injury. Their findings revealed that in 10 female handball and basketball injury situations a sudden valgus angle increase reached 12° with internal rotation abruptly increasing by 8° within the first 40 ms after initial ground contact. This period also corresponded with the average peak vertical ground reaction force of these 10 cases. Based on these findings, the group surmised that the ACL rupture likely occurred within this first 40 ms. Although this time window and that by Krosshuag, et al. (2007), in which ACL injury was estimated to occur between 17 – 50 ms after initial contact, does not allow for the production of maximal strength levels, our findings suggest that PT may perhaps provide clinicians an indicator of an athlete's ability to produce force rapidly (RTD) within that time frame. However, caution is warranted because our data are based on a single joint isometric strength testing protocol with no electromyography (EMG) information evaluating muscle activation patterns, thus our findings may not fully reflect the ability of an individual to rapidly generate force while performing a dynamic multi-joint task. Furthermore our results were based on a protocol in which PT and RTD were collected simultaneously and the participants were asked to contract as hard and as fast as possible. Traditionally, clinicians do not perform PT evaluations in this manner. Normally they allow for a longer ramp up time (2-3 seconds) for achieving maximum torque levels. In our protocol, participants would have achieved PT closer to 300 ms (Aagaard, et al., 2002; Andersen & Aagaard, 2006; Thorstensson, et al., 1976). This non-conventional method is arguably preferable given the nature of athletic competition where fast and short lasting movements allow for minimal time for the initiation and completion of the appropriate neuromuscular response (Caserotti, et al., 2008; Gruber & Gollhofer, 2004). Furthermore, the traditional methodological approach to evaluating PT may not reflect the same relationship with RTD as that used in the present study. Future studies should seek to explore this relationship between these two approaches.

In terms of strength endurance, our findings appear to indicate that an individual's maximum strength or ability to produce force rapidly does not influence this measure to a great degree. Although, these measures are preliminary, based on the minimal shared variance with PT and RTD, inclusion of measures of strength endurance into lower extremity strength testing batteries may be justifiable as PT and RTD do not appear to be indicative of strength endurance. However, future studies should seek to evaluate these relationships using isokinetic testing procedures to determine if these findings are similar under dynamic strength conditions.

Limitations

The author(s) do acknowledge the following limitations. First, since participants were not randomly sampled the findings of the experiment may only be limited to the sample, which was a sample of convenience. Second, although all participants were recreational athletes, varied athletic participation and years of experience may have influenced their performance on the computer-based strength testing.

Conclusion

The results of this study indicate PT is indicative of RTD at both the early and late phases, thus diminishing the necessity of having to evaluate both parameters. Our findings also indicate PT and SE are two independent measures. Thus, both should be evaluated when screening athletes for lower extremity strength deficits during PPEs and RTP scenarios.

CHAPTER V

Experiment III: The Relationship of Isometric Strength to Measures of Functional Performance

Title: The Relationship of Isometric Strength to Measures of Functional Performance

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CHAPTER V

Experiment III: The Relationship of Isometric Strength to Measures of Functional Performance

The assessment of proximal lower extremity muscular strength (i.e. hip and thigh strength) is of particular importance in sports medicine. Deficits in strength at the proximal musculature in combination with other injury related risk factors may place an individual at an increased risk for injuries such as noncontact anterior cruciate ligament ruptures (Claiborne, et al., 2006; Kollock, et al., 2008), patellofemoral pain syndrome (Niemuth, et al., 2005; Souza & Powers, 2009a, 2009b; Tyler, Nicholas, et al., 2006), and strains of the groin (Tyler, et al., 2001) or hamstring musculature (Croisier, et al., 2008). In order to help reduce the likelihood of injury to the lower extremity some have proposed the inclusion of lower extremity strength assessments into conventional preparticipation physical examinations (PPE) (Nadler, Malanga, et al., 2000; Scott, et al., 2004; Tyler, et al., 2001) and return-to-play (RTP) criterion (Augustsson, et al., 2004; Best & Brolinson, 2005; Hopper, et al., 2008; Neeter, et al., 2006) as a means of screening athletes for unilateral and bilateral strength deficits prior to play.

Within these two constructs (i.e. PPE and RTP) muscular strength can be measured statically or dynamically (e.g., isotonic and isokinetic testing) with factors such as cost, portability, and time needed to perform the evaluation often guiding the selection of a particular methodological approach (Kollock, et al., 2008). In these two clinical approaches to assessing athletic readiness, strength is defined as the ability of a muscle to create force through active tension (Hislop & Perrine, 1967). Strength is most often assessed clinically through maximum strength testing, however it is important to keep in mind that muscle strength, as a sensorimotor skill (Mebes, et al., 2008), has to be differentiated into separate aspects or parameters: maximum strength, rate of torque development (RTD), and strength endurance (Castro-Piñero, et al., 2010; Mebes, et al., 2008). Although each parameter evaluates a similar phenomenon (i.e. muscular strength), each targets a uniquely different function (or ability) of the muscle group over uniquely different intervals of time (Aagaard, et al., 2002; Andersen & Aagaard, 2006; Mebes, et al., 2008; Surakka, Romberg, Ruutiainen, Aunola, et al., 2004; Surakka, Romberg, Ruutiainen, Virtanen, et al., 2004).

In the past clinicians and researchers have assessed muscular strength through various techniques and instruments (Aagaard, et al., 2002; Bohannon, 1986, 1997b, 2005; Knapik, et al., 1983b; Kollock, et al., 2010; Ostenberg, et al., 1998). Broadly, these various techniques and instruments can be classified into tertiary (e.g. isokinetic instrumentation), secondary (e.g. portable isometric instrumentation), and primary (e.g. manual muscle testing) methods of assessment (Kollock, et al., 2008, 2010); for a further description of these three categories, readers are directed to Kollock et al. (2008). In many settings such as high school (Wham, et al., 2010) and small college athletic training departments, resources (e.g., equipment, time, and personnel) are limited and the cost to implement tertiary methods within their PPE and RTP situations may not be feasible.

In these types of clinical settings forms of secondary methods for muscular strength testing (e.g. isometric portable fixed dynamometry) may provide a less costly option. Computer-based isometric portable fixed dynamometry (PFD) has been proven as a reliable (Kollock, et al., 2010; Scott, et al., 2004) method for evaluating muscular strength. Earlier research conducted between 1980 and 2000 has reported observing very strong relationships (r = 0.70 to 0.89) between computer-based isometric and isokinetic instrumentation at low (60°/s) to mid (180°/s) isokinetic velocities (Hill, 1996; Jameson, et al., 1997; Knapik, et al., 1983b).

However, the question remains, does the use of portable computer-based isometric evaluations provide information unobtainable through less sophisticated and more cost effective primary methods (e.g. measures of functional performance such as single leg hopping tasks) for assessing muscular function within the construct of PPE and RTP situations. Health-care professionals often use functional performance test (FPT) batteries to evaluate lower limb function prior to return-to-play (Gustavsson, et al., 2006; Hopper, et al., 2008; Keays, et al., 2003). FPT batteries can encompass numerous components critical to sports participation such as strength (Hamilton, et al., 2008; Keays, et al., 2003), power (Hamilton, et al., 2008; Keays, et al., 2003), agility (Keays, et al., 2003), and muscular endurance (Gustavsson, et al., 2006; Itoh, et al., 1998) across multiple joints of the lower limb. Data reported within the literature indicates that FPTs have demonstrated significant correlations with isokinetic instrumentation at 60 and 180°/s, particularly at the knee flexors and extensors (Bjorklund, et al., 2006;

Hamilton, et al., 2008; Ostenberg, et al., 1998; Tsiokanos, et al., 2002). The triple hop test for distance was a strong predictor of isokinetic hamstrings and quadriceps strength at 60°/s and 180°/s, explaining 49-58.8% of the variance (Hamilton, et al., 2008). Findings within the literature comparing FPTs to computer-based isometric instrumentation are more varied indicating a small to strong relationship between the methods (Baker, et al., 1994; Jameson, et al., 1997). Baker et al. (1994) reported finding that isometric rate of force development during a unilateral leg extension prior to a 12 week strength training program demonstrated a trivial relationship to vertical jump height ($r = 0.098$) and moderate negative relationship to vertical jump work performed ($r = -.344$). Jameson et al. (1997) reported finding moderate correlations ($r = 0.54$, $p \leq 0.0001$) between one-leg vertical jump peak force measures and isometric peak force assessed at the knee extensors.

Unfortunately, much of the literature comparing FPTs and computer-based strength testing has been directed at the muscular function of the knee flexors and extensors. Currently, to the authors' knowledge, there exists no scientific data indicating the effectiveness of measures of functional performance in predicting isolated trunk and hip strength (e.g. hip abductor-adductor and hip external-internal rotator strength). Information into this area may aid in identifying and developing of feasible test batteries to screen athletes for unilateral and bilateral strength deficits within the traditional constructs of PPEs and RTP situations. Therefore, given the limited research into this area and the potential importance of including viable lower limb strength testing batteries into

PPEs and RTP situations to help reduce the risk of injury, the purpose of this experiment was to assess the relationships between FPTs and isometric computer-based evaluations of lower-limb muscle function (maximum strength, RTD, and endurance). The following hypotheses were proposed. The isometric strength parameters of maximum strength and RTD would have a positive correlation with the FPTs emphasizing distanced hopped and power. The isometric strength parameters of maximum strength (Ostenberg, et al., 1998) and RTD would have a negative correlation with the FPTs emphasizing endurance. There would be a significant positive correlation between isometric strength endurance and the FPTs emphasizing distanced hopped and power. Finally, there would be a significant negative correlation between the isometric strength endurance and FPTs emphasizing endurance.

Methodology

Study Design

We utilized a correlational design in which testing occurred over two test sessions. The first session consisted of advanced isometric assessments: maximum strength (peak torque), rate of torque development (RTD), and strength endurance for the hip abductor (AB), hip adductor (AD), hip flexors (HF), hip extensors (HE), hip external rotators (ER), internal rotators (IR), knee flexors (KF), and knee extensors (KE). The peak torque (PT) and RTD were collected simultaneously and prior to the assessments of strength endurance. The main outcome measures included absolute and normalized PT and RTD at four separate time intervals (0-30, 0-50, 0-100, and 0-200 milliseconds), and fatigue index (FI) ratio score (i.e. measure of strength endurance) for each muscle group evaluated.

The second session consisted of measures of functional performance: single leg vertical jump (SVJ), single leg hop for distance (SLHD), triple hop for distance (THD), crossover hop for distance (CHD), and the 30 s lateral hop test for endurance. The main outcome measures for the measures of functional performance included the following: SLHD distance [cm], SLHD work performed, THD distance [cm], THD work performed, SVJ height jumped [cm], SVJ work performed, CHD distance [cm], and the number of hops performed during the 30 s lateral hop test for endurance.

Participants

Sixty-two physically active recreationally athletic (mass, 74.63±14.79 kg; height, 171.23 cm±10.72; age, 21.05±2.82) males (N=30) and females (N=32) were recruited. A recreational athlete was defined as an individual engaged in moderate activity, such as tennis, biking, jogging, weight lifting, etc, 2-3 times a week for at least 30 minutes. Individuals were excluded if they had any of the following conditions: 1) an ACL tear within the last two years 2) restricted within the last six months by an athletic trainer or team physician from participating in any practice or competition for longer than two days because of a lower extremity injury, or 3) a neurological disorder. Participants were asked not to perform a rigorous lower extremity workout at least 24 hours prior to testing. All measures were collected on the dominant limb. Limb dominance was determined by asking the subject which leg they would use to kick a soccer ball, using their maximal force effort. Participants read and signed a consent form that was approved by the institutional review board.

Instrumentation

Isometric Strength Assessment. Isometric strength data were collected using a commercial dynamometer (Model: LCR, OmegaDyne, Inc, Stamford, CT). The data were sampled at 1000 Hz (PT and RTD) and 100 Hz strength endurance using a 1 MHz, 24 bit USB Data Acquisition Module (Model: NI-DAQ 9237, National Instruments Corporation, Austin, TX) and logged using LabVIEW Signal Express (National Instruments Corporation, Austin, TX) . The data acquisition module converted the voltage received from a load cell to strain (National Instruments Corporation Technical Support, personal communication, February 3, 2010). Strain was scaled to quantities of force in pounds [lbs] using a series of 38 known weights (loads) ranging from 5 to 213.2 lbs (22.5 to 959.4 N). Force in pounds [lbs] was later converted to Newtons [N]. All logged data were stored on a laptop computer for offline processing and analysis. The data were filtered post log using a digital fourth order butterworth filter with an optimal cutoff frequency developed within LabVIEW Signal Express. A power spectrum density (PSD) analysis was performed using a custom Matlab (The MathWorks Inc., Natick, MA) program to determine the optimum cut-off frequency of 50 Hz. The researcher(s) verified the load cell was within (1%) of a known weight (178 N) daily to ensure reliability.

Testing Procedures

For session one, the subjects reported to the Sports Medicine Research Laboratory in athletic attire for one testing session. Anthropometric measures (mass, height, shank length, and leg length) were obtained, and the subjects were instructed to perform a 10-minute warm-up on an exercise bike. For the isometric strength parameters of maximum strength (i.e. PT) and RTD, the participants performed 3 test trials, each 5 seconds(s) in duration, with a 60 s rest period between each trial. The muscle groups were evaluated in a counterbalanced order. Scripted instructions and prompts were used.

Following the PT and RTD strength analyses the subject was given a 10 minute rest period. Immediately following the rest period, subjects underwent isometric strength endurance testing, which evaluated the same muscle groups tested during the PT and RTD analyses. The strength endurance testing was performed in the same testing positions as the PT and RTD analyses. For the strength endurance testing subjects performed two isometric contractions, each for 30 s. Each 30 s contraction was separated by a two minute rest period. In order for a trial to be deemed valid, the subject had to reach a minimum of 95% of their maximal isometric PT (as determined by the previous PT analyses) within the initial five seconds of the start signal. If this criterion was not met within the initial five seconds the attempt was halted after the initial five seconds and the subject was allowed a two minute rest period. This minimum of 95% of PT requirement was adopted to ensure that the subjects were giving a maximal effort at the start of each contraction. As with the PT and RTD analyses the muscle groups were evaluated in a counterbalanced order and scripted instructions and prompts were used. The strength endurance scripted instructions and prompts were similar to the maximum strength and RTD script with the exception of asking the participants to "keep pulling" approximately every 5 sec until completion of the task.

For session two, the subjects reported to the Sports Medicine Research Laboratory in athletic attire for testing. The subjects were instructed to perform a 10-minute warm-up on an exercise bike. For the functional performance test battery, the participants performed 3 test trials for each task with a 2 minute rest period between each test. The functional performance test battery was administered in a counterbalanced order.

Standing Isometric Hip Protocol. AB, AD, HE, and HF were assessed in a standing position. The participants stood with feet shoulder width apart with the load cell attached to the appropriate anatomical aspect (i.e. medial [AB], lateral [AD], anterior [HE], and posterior [HF]) of the lower leg proximally above the medial malleolus via an ankle cinch strap (figures 4.1 and 4.2) (Kollock, et al., 2010).

Seated Isometric Strength Protocol. KE, KF, ER, and IR were performed in an upright-seated position. The hip and knee of the test extremity were positioned in 90 °of knee flexion so that the tibia of the test extremity was perpendicular to the floor. The load cell was attached to the appropriate anatomical aspect (i.e. posterior [KE], anterior [KF], lateral [ER], and medial [IR]) of the lower leg proximal to the medial malleolus via an ankle cinch strap (figures 3 and 4) (Kollock, et al., 2010).

30 s Lateral Hop Test for Endurance. Two parallel strips of tape, 40 centimeters apart, were placed on the floor. The parallel strips were placed in an anterior-posterior direction in relation to the limb of the participant's body. The participants were instructed participant to stand on one foot with the arms behind the back and to jump side to side between the parallel lines. The task lasted for 30 seconds. All jumps were performed without touching the tape, or they were counted as an error. If 25% or more of the jumps were counted as errors, the test was performed after a 3-minute rest period (Gustavsson, et al., 2006). Gustavsson, et al. (2006) reported that 30 second lateral hop test displayed a higher sensitivity (.77), specificity (.87), and reliability (ICC=.72 -.95) than the square hop test for endurance.

The Triple Hop for Distance. The participant was instructed to stand on one leg and perform 3 consecutive hops as far as possible landing on the same leg. The total distance of the 3 consecutive hops were recorded (Reid, et al., 2007; Ross, Langford, et al., 2002). During the task performance the participant's arms were free from restraint and able to be used help both propel the body and balance upon landing. Ross, et al. (2002) reported an $ICC_{(2,3)}$ of 0.97 with a SEM of 11.17 cm.

Crossover Hop for Distance. The crossover hop test consisted of an 8-meter tape strip on the floor. The participants were instructed to hop forward 3 consecutive times while alternately crossing over the marking. The participants were instructed to position themselves such that the first of the 3 hops were lateral with respect to the direction of crossover (Reid, et al., 2007; Ross, Langford, et al., 2002). The total distance hopped forward was recorded. The participant's arms positioning was similar the criteria used in the triple hop for distance test. Ross, et al. (2002) reported intra-session values of 93 with an SEM of 17.74.

Single Leg Hop Test for Distance. The participant was given 1-2 practice trials and three successful test trials. The participant was positioned at the starting position on one leg with the hands behind the back (Ostenberg, et al., 1998; Ostenberg & Roos, 2000) to minimize potential for performance of a countermovement the participant was required to keep his or her hands behind their back. The subject was then instructed to jump with a maximal effort as far as possible and the distance from the great toe at starting position to the heel at landing was measured and recorded. The furthest hop of the test trials was recorded as the maximum hop (Ostenberg, et al., 1998; Tegner, et al., 1986). This test was described and tested for intra-session reliability ($ICC_{2,1}$ =.97, SEM = 5.93 cm) by Booher, et al. (1993). The intra-session reliability was also evaluated by Ross, et al., (2002) who reported an $ICC_{(2,3)}$ of 0.92 with a SEM of 4.61 cm.

Single Leg Vertical Jump. The participant was positioned with their right shoulder six inches away from a vertical jump measuring device. The participant raised their right hand and touched a plastic strip on the measuring device. After the reach height was recorded, the participant was instructed to lower the hand and stand on one leg. The participant was instructed to jump with maximal effort as high as possible, strike a plastic measuring strip with the right hand, and land on the take-off foot. Participants were given three test trials and the highest jump was recorded as the maximum vertical jump.

Data Reduction and Normalization

The isometric strength data were reduced in the following manner. Force [N] was then used to calculate torque [Nm] using the following equation: torque = *moment arm* [m] x force [N], where the *moment arm* is the distance between lateral malleolus and the joint axis of rotation. This distance was represented by the shank or leg length measures. The highest value of the three isometric attempts was used to determine the maximum strength (i.e. absolute peak torque [Nm]) and absolute RTD [Nms^{-1}]. The initial 200 milliseconds after the onset of the contraction were used to calculate the absolute RTD across four separate time-periods (0-30, 0-50, 0-100, and 0-200 ms) (Aagaard, et al., 2002; Christensen, et al., 2008). The point at which the torque is 7.5 Nm greater than the baseline value was defined as the onset of the muscle contraction (Aagaard, et al., 2002). Absolute PT and RTD were collected during the same test trial. The absolute strength measures represent the force data prior to normalizing the data relative to height and weight. Absolute peak torque [Nm] and RTD [Nms^{-1}] were both normalized relative to weight and height via the following equations: a) Normalized PT = PT [Nm]/(weight [N] x height [m]) x 100 (equation 3.1) (Bolgla, et al., 2008; Boling, et al., 2009; Krause, et al., 2007) and b) Normalized RTD = RTD [Nms^{-1}]/(weight [N] x height [m]) x 100 (equation 4.1).

Strength endurance was determined through a fatigue index (FI) ratio score: FI = (1 – (AUTC / HAUTC)) x 100 (equation 4.2) (Meldrum, et al., 2007;

Sanjak, et al., 2001; Schwid, et al., 1999; Surakka, Romberg, Ruutiainen, Virtanen, et al., 2004), where FI is equal to 1 minus the quotient of the area under the force-time curve (AUFC) divided by the hypothetical area under the force-time curve (HAUFC). The AUTC is the integral of force for a 30-second trial time, while the HAUTC is the peak force value observed between 0-5 seconds of the 30-second trial time. A lower fatigue index score indicates a greater resistance to fatigue. For the SVJ, THD, SLHD tasks the work performed was calculated by taking the distance hopped in meters [m] and multiplied by the mass [kg] of the subject times gravity:

work in joules [J] = participants mass [kg] x gravity [9.81 m/s^2] x distanced hopped [m]..Equation (5.1)

(Baker, et al., 1994).

Statistical Analysis

Separate Pearson product moment bivariate correlations were used to evaluate the association between isometric muscular performance and functional performance. The alpha level was set *a priori* at $p \leq 0.05$. The scale set forth by Hopkins (2002) was used to interpret all correlation coefficients: trivial (0.0), small (0.1), moderate (0.3), strong (0.5), very strong (0.7), nearly perfect (0.9), and perfect (1.0). All coefficient correlations (r -values) were squared to calculate the coefficient of determination (r^2) in order to evaluate the percent of common variance between any two variables.

Results

Functional Performance and Absolute PT

The means and standard deviations for the FPT are described in table 5.1. The correlation coefficients for the relationship between measures of functional performance and absolute PT are detailed in table 5.1. All measures of PT demonstrated a significant moderate to very strong positive correlation (r=.358-.792) to measures of functional performance with the exception of the association (r=.260-.288) of the 30 s lateral hop test for endurance to AB, HE, ER PT. THD forefoot and rear foot measures displayed very strong positive correlations with the greatest number of absolute PT measures. THD measured at the forefoot demonstrated a very strong positive correlation with was six of eight PT measures: AB (r=.792, p≤0.001), AD (r=.784, p≤0.001), HE (r=.701, p≤0.001), HF (r=.763, p≤0.001), KE (r=.734, p≤0.001), and ER (r=.704, p≤0.001). THD forefoot measures accounted for 49.1% - 62.7% of the variance in the PT of the aforementioned variables. THD measured at the rear foot displayed a very strong positive correlation with five of eight absolute PT measures: AB (r=.774, p≤0.001), AD (r=.774, p≤0.001), HE (r=.706, p≤0.001), HF (r=.747, p≤0.001), and KE (r=.703, p≤0.001) accounting for 49.4% - 59.9% of the variance. The only measure of functional performance to display a very strong positive correlation to KF PT was SVJ Work (r=.714, p≤0.001).

Functional Performance and Absolute RTD

The correlation coefficients for the relationship between measures of functional performance and absolute RTD [Nm/s] are detailed in tables 5.3-10. Functional performance measures demonstrated a moderate to very strong positive correlation (r=.345-.771) to absolute RTD with the exception of the association (*r*=.218-.280) of 30 LHE to both AB and HE RTD at four separate time intervals. Additionally, the SVJ [cm] demonstrated a small positive correlation (*r*=.287-.290) to HE RTD collected at each of the four separate time intervals. The work performed for the forefoot measure for both THD and SLHD and THD rear foot measure demonstrated a very strong positive correlation to AB (*r*=.737-.771, $p \leq 0.001$) and AD (*r*=.701-.715, $p \leq 0.001$) RTD at each of the four separate time intervals, accounting for 49.1% - 59.4%. The work performed for the SLHD rear foot measure demonstrated a very strong positive correlation (*r*=.701-.702, $p \leq 0.001$) AB RTD from 0-30, 0-50, and 0-100 ms, accounting for approximately 49% of the variance.

Functional Performance and Normalized PT

The correlation coefficients for the relationship between measures of functional performance and normalized PT are detailed in table 5.2-10. The correlation coefficients ranged from trivial to strong (0.0-.599). Both the rear and forefoot measures of hop distance [cm] for the THD and SLHD demonstrated a strong positive correlation with AD normalized PT. The THD [cm] front measures also displayed a strong positive correlation with HF (*r*=.523, $p \leq 0.001$) and KE (*r*=.518, $p \leq 0.001$) normalized PT accounting for 26.8 and 27.3% of the variance respectively. The SLHD [cm] rear foot measure demonstrating a strong positive correlation (*r*=.519, $p \leq 0.001$) to HF normalized PT accounting for 26.9% of the variance in HF. In addition, SVJ [cm] displayed a strong positive correlation (*r*=.515, $p \leq 0.001$) to KF normalized PT accounting for 26.5% of the variance, while the 30 LHE demonstrated strong positive correlations to both AD (*r*=.507,

$p \leq 0.001$) and KF (r=.502, $p \leq 0.001$) normalized PT accounting for 25.2% - 25.7% of the variance.

Functional Performance and Normalized RTD

The correlation coefficients for the relationship between measures of functional performance and normalized RTD are detailed in tables 5.3-10. The correlation coefficients ranged from small to strong (r=.103 - .525). The highest relationships between the 30 s hop test for endurance (30 LHE) and the AD (r=.510-.517, $p \leq 0.001$), HF (r=.493-.520, $p \leq 0.001$), and KF (r=.510-.521, $p \leq 0.001$) normalized RTD at the four separate time intervals accounting for 24.3% - 27.1% in the aforementioned measures.

Functional Performance and Strength Endurance

The correlation coefficients for the relationship between measures of functional performance and strength endurance are detailed in tables 5.3-10. The correlation coefficients ranged from trivial to small, with several measures of functional performance demonstrating a negative relationship to isometric strength endurance. There was no significant correlation between any of the measures of functional performance and isometric strength endurance at the musculature of the hip and thigh.

Discussion

The main finding of our study was that the work performed by participants during SVJ, THD, or SLHD task was, in general, strongly related to an individual's maximum strength and their ability to rapidly develop force. These results suggest that these FPTs may be strong indicators of PT and RTD in recreationally athletes. However, FPTs used in the present study were not strongly related to isometric muscular endurance.

The association of FPTs emphasizing muscular strength and power to PT and RTD

Although isometric instrumentation may be a less expensive option as opposed to isokinetic instrumentation, the additional resources (e.g., money, time, and special personnel to perform data analysis) needed may not be an absorbable cost and justifiable use of clinician time in certain clinical settings. Thus, the purpose of this experiment was to assess the relationships between FPTs and isometric computer-based evaluations of lower- limb muscular strength. Since there is limited research into the relationship of FPTs to isometric strength, our hypothesis was based on earlier literature in which FPTs were reported as predictors of isokinetic knee strength (Hamilton, et al., 2008; Ostenberg, et al., 1998). Based on this literature, we hypothesized that FPTs emphasizing distance and power would demonstrate a significant positive correlation to PT and RTD. Our results partly supported this hypothesis.

We observed that the following FPTs demonstrated a moderate to very strong relationship to both absolute PT and RTD: SVJ, CHD, THD, and SLHD. However, when PT and RTD were corrected for height and weight the relationship decreased. We corrected our isometric PT and RTD to avoid the assumption that the strength of the associations was merely a reflection of participant body size (Andersen & Aagaard, 2006; Ostenberg, et al., 1998). The findings between the distance hopped during FPTs and absolute PT are in line with prior literature (Bjorklund, et al., 2006; Hamilton, et al., 2008; Tsiokanos, et al., 2002). The strongest relationships in regards to distance hopped and absolute strength were observed between the THD forefoot measure and absolute AD, HF, KE PT. In terms of relationship between THD distance hopped and KE PT, stronger relationships have been reported at this muscle group using isokinetic instrumentation (Hamilton, et al., 2008). Hamilton, et al. (2008) reported THD distance as a strong predictor of isokinetic knee hamstrings and quadriceps strength at 60 and 180°/s predicting 58.5% and 49% of the variance, respectively. Our findings revealed that THD distance accounted for 36.3 - 42.6% of the variance in absolute isometric KE PT and 30.1 – 35.1% of the variance in isometric KF PT. One explanation is perhaps the difference in neural recruitment patterns between static and dynamic tasks (Baker, et al., 1994; Murphy & Wilson, 1996). Findings within the literature suggest that neural recruitment (Baker, et al., 1994; Murphy & Wilson, 1996; Wilson & Murphy, 1996) and rate coding (Baker, et al., 1994) differ between static and dynamic tasks, thus it is plausible that neural recruitment patterns elicited by isokinetic mode contractions more closely resemble that of the triple hop task. Ostenberg, et al. (1998) reported a predicted variance closer to that of Hamilton, et al. (2008), reporting that THD distance predicted 43% and 52% of the variance in isokinetic KE PT at 60°/s and 180°/s, respectively. However, that predicted variance represented the total model. The partial correlation coefficients after correction for body weight, height, and age ranged between .30 and .46 at 60 and 180°/s, respectively for the association to THD distance. This closer approximation to the relationship we observed within the present study in which THD distance demonstrated a significant moderate to strong (*r* = .431 - .518, *p*≤0.01) relationship to normalized PT is arguably an outcome of correcting the PT for height and weight. Normalizing strength data across studies would provide a better means for comparing the results of opposing investigations.

Our most important findings in regards to the THD task was that it displayed its strongest associations to absolute PT when it was evaluated as work performed in joules. The findings revealed that when performance of the THD was quantified in terms of work, it accounted for 40% - 62.7% of the variance in AB, AD, HE, HF, KE, and ER PT. We also observed similar findings in the relationships of the THD work performed to AB and AD RTD at separate time intervals. This observation in the relationship of THD to PT and RTD was not surprising given the strong relationship reported between PT and RTD in previous literature (Andersen & Aagaard, 2006; Mirkov, et al., 2004). This relationship between PT and RTD was also observed in our study in a separate analysis of the data.

To our knowledge, the present study was the first to compare single joint isometric strength to the work performed during single leg hopping tasks. Baker, et al. (1996) evaluated this relationship using a unilateral isometric leg extension task and the double leg vertical jump task. The group reported that vertical jump work demonstrated a negative correlation (*r*=-.344 and -.328) to RTD at both the pre and post strength training regimen test sessions. In contrast, we observed that the SVJ work demonstrated a significant strong positive correlation (*r*= .520 - .679, *p*≤.001) to RTD. We hypothesize that differences in outcome are task related. Isometric strength in the former study was assessed using a seated unilateral leg extension protocol, while we assessed the muscle groups of the hip and thigh separately using single joint test procedures. The seated unilateral leg extension protocol may have allowed for a greater dependency on muscle groups such as the KEs and plantar-flexors as opposed to the proximal musculature of the trunk and hip. Other musculature such as the HEs, ABs, and ADs, may be important contributors to the amount of work capable of being performed during the vertical jump task. Second, because the SVJ requires the participant to hold and stabilize upon landing on a single limb, it potentially places a greater demand on the frontal plane musculature of the hip. Thus, the SVJ may be preferable to double leg vertical jump because it may provide clinicians the ability to better challenge the musculature of the ABs and ADs while also allowing for individual limb evaluation.

The association of FPTs emphasizing muscular endurance to PT and RTD

Our second hypothesis was that isometric strength parameters of maximum strength (Ostenberg, et al., 1998) and rate of force development would have a negative correlation with the FPTs emphasizing endurance. Our findings do not support this hypothesis. In general, the 30 s lateral hop test for endurance demonstrated moderate to strong positive associations to absolute and normalized PT and RTD, with the exception of absolute AB, HE, and ER and normalized ER PT and RTD. This perhaps suggests that the high PT and RTD may result in an increase number of repetitions, thus a better performance in the 30 LHE. However, given the minimal percentage of common variance observed it appears that 30 s lateral hop test for endurance is not an indicator of an individual's maximum strength or an ability to generate force quickly (i.e. RTD). In an earlier study Ostenberg, et al. (1998) reported that the square hop test for endurance showed, at best, a small association to isokinetic KE PT tested at 60°/s and 180°/s with partial correlation coefficients after correction for weight, height, and age of -.09 and .13, respectively (Ostenberg, et al., 1998). Our findings in regards to isometric KE PT and the FPT for endurance displayed a moderate association regardless of weight or height correction. This difference in results between our study and Ostenberg, et al. (1998) may be a result of differing testing protocols. Arguably, the square hop test is a more challenging task than the 30 s lateral hop test for endurance because it requires medial, anterior, and posterior movements as well as lateral movements. This would presumably lend to a greater number of errors (or rejected hops) resulting in less valid repetitions as opposed to the 30 s lateral hop test for endurance. Thus, it is possible that the range of the valid repetitions performed in each study could have contributed to the differences in results.

The association of FPTs to isometric strength endurance

In our third hypothesis, we proposed that there would be a positive correlation between the isometric measure of endurance and the FPTs emphasizing distance and power, however this hypothesis was not supported by our results. Additionally, our hypothesis that there would be a significant correlation between the isometric strength endurance and the FPT for endurance was not supported. Several factors may have contributed to these findings. First, FPTs such as SVJ, CHD, THD, and SLHD are functional integrated tasks executed over a brief period, thus they may be largely influenced by body size, maximum strength, acceleration, movement velocity, coordination, and postural control (Ostenberg, et al., 1998). Mechanically, the rapid execution of FPTs, as with other dynamic movements, could permit for the utilization of the stretch – shortening mechanism allowing the use of elastic energy to influence or contribute to performance (Baker, et al., 1994). Second, the relationship between the FPT emphasizing endurance and the isometric strength endurance test may be a result of the individual task requirements. The more functionally integrated FPT may have allowed the participant to compensate for fatigue because the muscles were able to act synergistically across the whole of the lower limb to accomplish the task. It is plausible that because the isometric endurance task isolated one particular muscle group the participant was more susceptible to peripheral fatigue mechanisms. Although the 30 s may be sufficient to fatigue a muscle group under isolated conditions, longer time durations (e.g. 45 -50 s) could be required to elicit the notable effects of fatigue during functional integrated tasks such as the 30 s lateral hop test for endurance in healthy recreationally active individuals.

Clinical Relevance

Clinically, the use of FPTs represents a more time-efficient and cost-effective method of assessing muscle function when compared to isometric or isokinetic instrumentation (Clark, 2001; Hamilton, et al., 2008). This is because FPTs normally require minimal materials (Hamilton, et al., 2008), space, time (Hamilton, et al., 2008), and personnel for test administration (Clark, 2001), making their use attractive for inclusion in PPEs and RTP scenarios (Clark, 2001). FPTs and single–joint dynametric testing procedures represent uniquely different methodological approaches (i.e. integration versus isolation) to evaluating muscular function. FPTs assess the function of the entire lower limb in an integrated manner encompassing strength, power, neuromuscular coordination, and stability across multiple joints (Docherty, et al., 2005; Hamilton, et al., 2008; Keays, et al., 2003), all of which is occurring at varied movement velocities. This is in contrast to the single joint strength testing, under fixed velocity conditions of isometric or isokinetic instrumentation. However, our findings demonstrated that when accounting for weight through the calculation of work performed, the THD and SLHD tasks displayed a strong to very strong relationship to absolute PT and RTD in recreationally active individuals. The possible ability of these tasks to identify AB and AD weakness may add to their clinical usefulness within PPEs and RTP scenarios. However, future research is needed to validate THD and SLHD work performed as predictors of AB and AD maximum strength and rapid force production. Finally, although the FPT used to evaluate endurance was not found to be associated to isometric strength endurance, further work is needed in this area exploring this relationship using FPTs conducted over longer durations (e.g. 45 – 50 s). This increased time duration may be necessary to induce some fatigue mechanism at the lower limb when performing FPTs designed to emphasize endurance such as the 30 s lateral hop test for endurance.

Limitations

The author(s) do acknowledge the following limitations. First, since participants were not randomly sampled the findings of the experiment may only be limited to the sample, which was a sample of convenience. Second, although all participants were recreational athletes, varied athletic participation and years of experience may have influenced their performance on both the computer-based strength and functional performance test batteries.

Conclusion

FPTs are popular because they require minimal materials (Hamilton, et al., 2008), space, time (Hamilton, et al., 2008), and personnel for test administration (Clark, 2001), which make them ideal for use during PPEs and RTPs situations (Clark, 2001). The results of this investigation indicate that potential exists for clinicians to screen athletes quickly for bilateral and unilateral weakness and deficits in rapid force production at the lower limb using the work calculated through the performance of the THD task. However, further investigation is needed into these relationships to validate their use as a potential predictor of muscular strength at the individual muscles at the hip and thigh.

CHAPTER VI

CONCLUSION

Overall, these three experiments indicate that in PPEs and RTP evaluations where tertiary methods might not be feasible, secondary and primary methods for evaluating muscle function may present a viable option for evaluating an individual's maximum strength and or rapid torque production. In the first experiment, we found that at the hip musculature, absolute isometric PT demonstrated a strong to very strong relationship to isokinetic PT evaluated at 60°/s. At the HE, HF, AD, and ER musculature, absolute isometric PT accounted for 60% - 75% of the variance in isokinetic PT at this velocity. However, the strength of these associations did decrease after torques were corrected (i.e. normalized) for weight and height. Our findings suggest, especially in regards to normalized IR, that other factors (e.g. gender, age, movement velocity, and amount of joint excursion allowed) not accounted for in our study design may have had an influence on isokinetic PT outcomes. Therefore, caution is warranted when substituting computer-based isometric PT testing for that of isokinetic PT evaluations at 60°/s. However, further research is needed before definitive conclusions can be made in regards to the substitution of portable fixed computer-based isometric testing for low velocity isokinetic instrumentation.

The second experiment determined that it might not be necessary to assess all three aspects of muscular strength. Our findings suggest that maximum strength appears to be a very strong indicator of an individual's ability to produce force rapidly, but not in their ability to sustain maximum levels of strength for prolonged periods. Our data further suggests that unlike experiment one body size minimally influenced these relationships. Based on the information obtained from experiment two, it appears that clinicians should obtain information on both maximum strength and endurance when using portable fixed computer-based isometric testing procedures.

In our third and final experiment, we compared isometric strength to a battery of single leg hopping tasks. The findings from experiment three suggested that tasks such as the SVJ, THD, and SLHD might be viable substitutes for determining maximum strength at the hip and thigh musculature. Our findings indicate that when accounting for weight through the calculation of work performed, tasks such as the SVJ, THD, and SLHD provide a better indicator of an individual's maximum strength and rapid force production than a simple distance hopped measure. Another observation of potential importance was that the work performed during the THD task accounted for 49% - 62.7% of the variance in frontal plane hip (i.e. AB and AD) maximum strength and rapid force production (i.e. RTD), adding to the already reported clinical usefulness of the task (Hamilton, et al., 2008). Finally, the FPT emphasizing endurance in the present study accounted for very little of the variance in isometric endurance, suggesting that the 30 s lateral hop test is not a strong indicator of the fatigability of an isolated muscle group. It is plausible that the single joint isometric endurance test was more susceptible to fatigue over a 30 s period because it isolated one particular muscle group as opposed to the more functionally integrated FPT. Thus, it may be that FPTs designed to measure endurance need to be performed over greater periods (e.g. 45- 50 s) in order to elicit the effects of fatigue in healthy individuals. Future studies should seek to address this concern.

In conclusion, the present investigation and those by prior researchers illustrate the potential clinical usefulness of secondary and primary methods for evaluating the lower extremity musculature within the context of PPEs and RTP evaluations. However, further research is required. The present study was powered (.80) to explore the association between these different clinical methods for evaluating lower extremity muscle function via multiple Pearson's (*r*) correlations and therefore provide only insight into this area and not into cause and effect relationships. Future investigators should seek to design studies powered for the use of predictive models to determine if there exists a cause and effect relationship. Future studies should also account for other factors not addressed in this present study such as gender and age.

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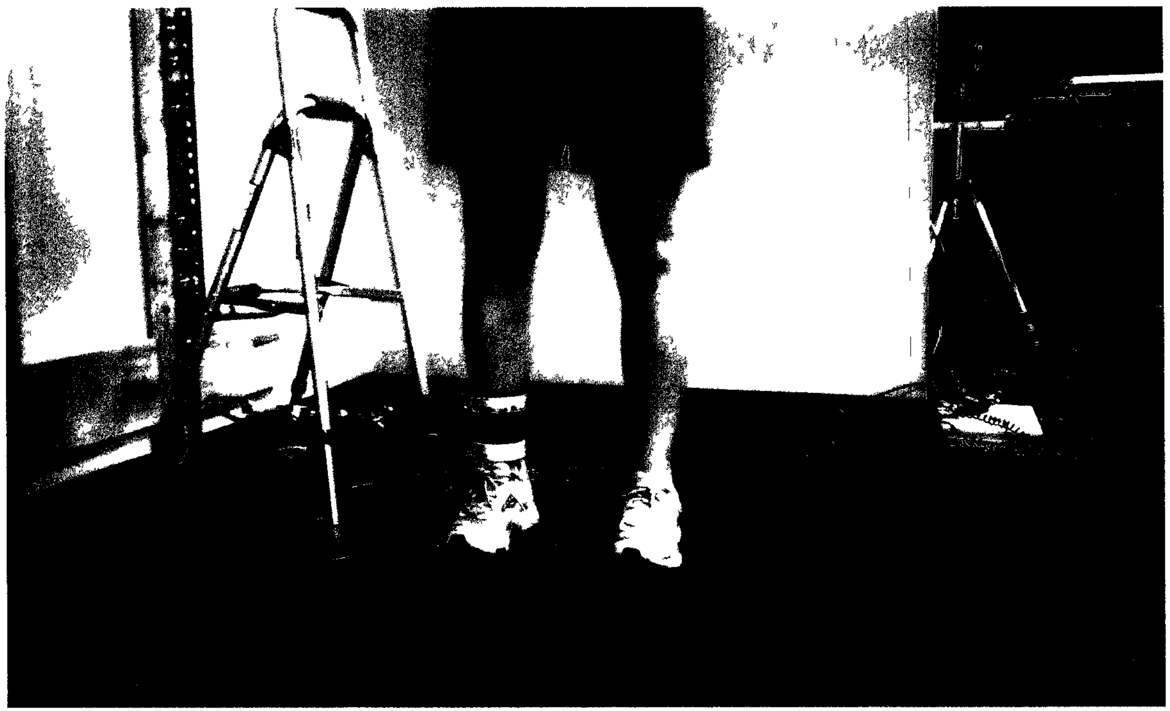
APPENDICES

Appendix I – Table 2.1. Functional Performance Testing Reliability and Normative Data Chart

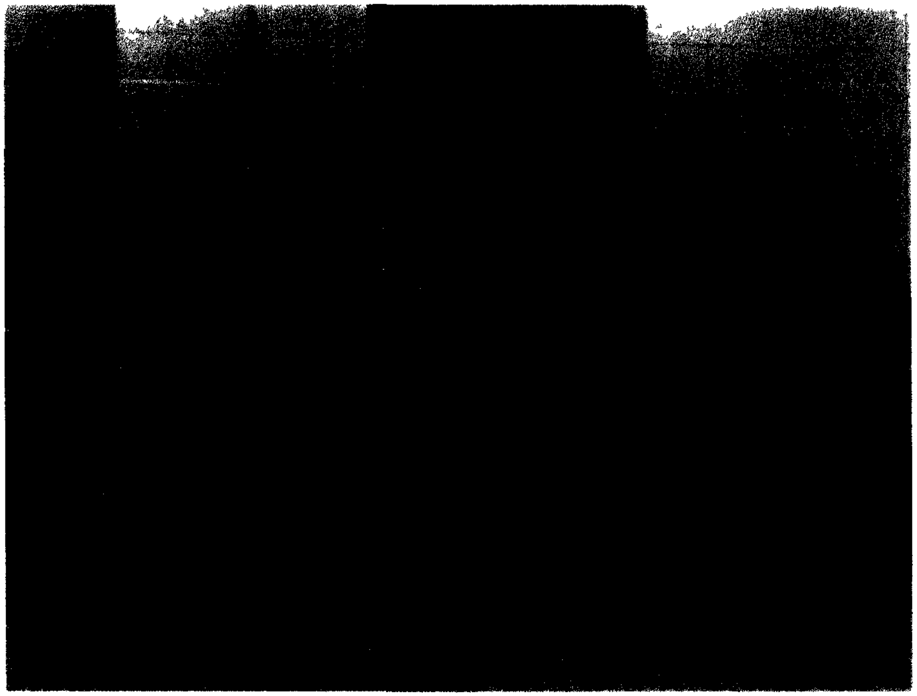
Study	Task	Sample Population	Limb Tested	Gender	N	Mean	SD	ICC	SEM
Gustavsson, et al 2006	SLHD	healthy subjects	right and left	M	9	160	±11 cm	0 86 - 0 91	
				F	6	137	±13 cm	0 88 - 0 98	
Ross, et al 2002	SLHD	United States Air Force Cadets	randomly selected	M	18	208 24	±16 30 cm	0 92	4 61
Kovaleski et al 2001	SLHD	uninjured	dominant	M(15) F(15)	30	164 59	±31 7 cm		
Itoh, et al 1998	SLHD	healthy controls	dominant	M	23	1 93	±0 19 m		
			dominant	F	37	1 84	±0 18 m		
Ostenberg, et al 1998	SLHD	female soccer athletes	dominant	F	101	131 00	±13 cm		
Booher, et al 1993	SLHD	not stated	right and left	M(4),F(14)	18	156 03	±35 95 cm	0 97	5 93
Hamilton et al 2008	THD	NCAA DI Soccer Athletes	dominant	M(20) F(20)	40	547 20	97 cm		
Ross,et al 2002	THD	United States Air Force Cadets	randomly selected	M	18	673 35	±66 cm	0 97	11 17
Ostenberg et al 1998	THD	female soccer athletes	dominant	F	101	508 60	±47 cm		
Ross, et al 2002	CHD	United States Air Force Cadets	randomly selected	M	18	649 19	±69 29 cm	0 93	17 74
Clark et al 2002	CHD	physical therapy students	dominant	M(4) F(8)	12	601 60	±117 6 cm	0 94	28 8
Gustavsson, et al 2006	30-HTE	healthy subjects	right and left	M	9	55 00	±6 reps	0 72 - 0 78	

M=male F=female, N=number of subjects SD=standard deviation ICC=intra-class correlation coefficient
SEM= standard error of measure SLHD=single leg hop for distance THD=triple hop for distance, CHD=crossover hop for distance
30-HTE=30 second lateral hop test for endurance

Appendix II – Figure 3.1. Hip Adduction Evaluated with PFD



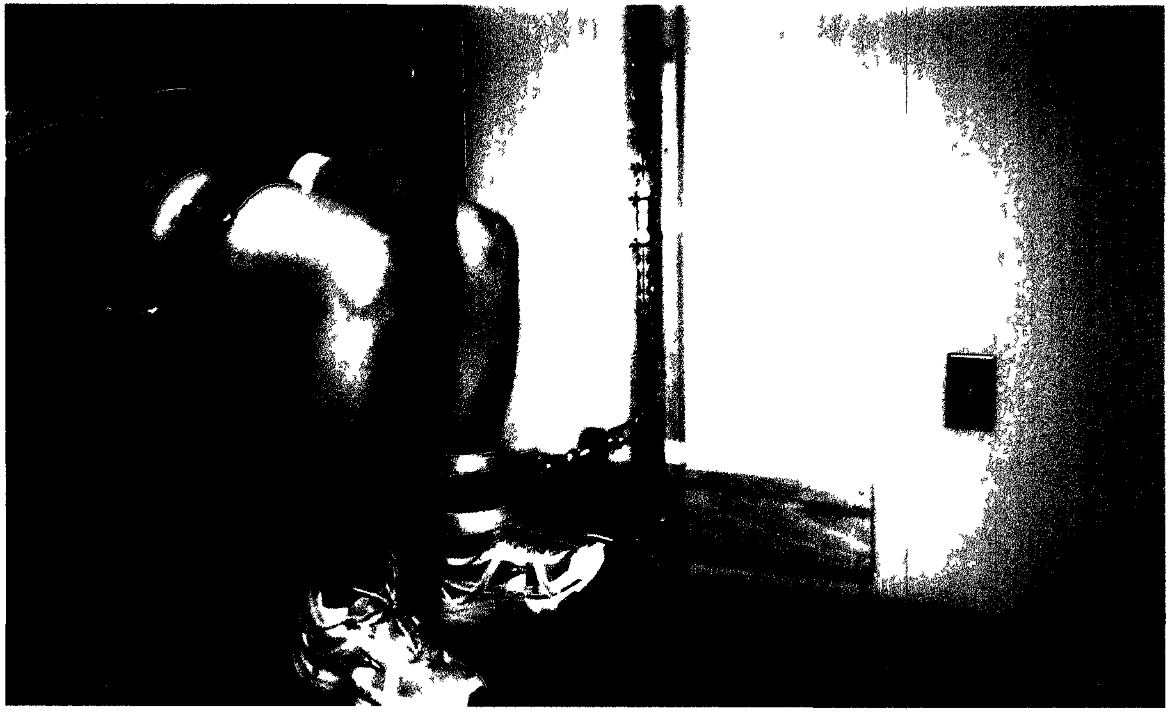
Appendix III – Figure 3.2. Isokinetic Hip Flexion



Appendix IV – Figure 3.3. Isokinetic Hip Abduction

Appendix V – Figure 3.4. Isokinetic Hip External Rotation

Appendix VI – Figure 3.5. Isometric Hip External Rotation Evaluated with PFD



Appendix VII – Table 3.1. Absolute and Normalized Isokinetic and PT Means

		Mode (Nm)				Mode (Normalized)			
		PFD		Isokinetic		PFD		Isokinetic	
Muscle Group	Gender	*mean*	*±sd*	*mean*	*±sd*	*mean*	*±sd*	*mean*	*±sd*
Hip Extensors	M	172.86	61.09	92.15	24.56	11.11	2.62	6.04	1.48
	F	90.10	26.09	54.02	9.39	9.24	1.67	5.60	1.28
	T	131.48	62.36	73.09	26.65	10.17	2.74	5.82	1.41
Hip Flexors	M	162.93	1.01	111.86	14.17	10.55	2.86	7.36	1.01
	F	92.74	19.46	64.24	9.45	9.55	2.21	6.64	1.19
	T	127.84	53.88	88.05	27.14	10.05	2.53	7.00	1.19
Hip Adductors	M	158.39	49.44	66.03	30.51	10.32	2.89	4.23	1.63
	F	91.13	25.22	42.57	12.06	9.37	2.60	4.31	1.28
	T	124.76	51.45	54.30	25.54	9.84	2.71	4.31	1.42

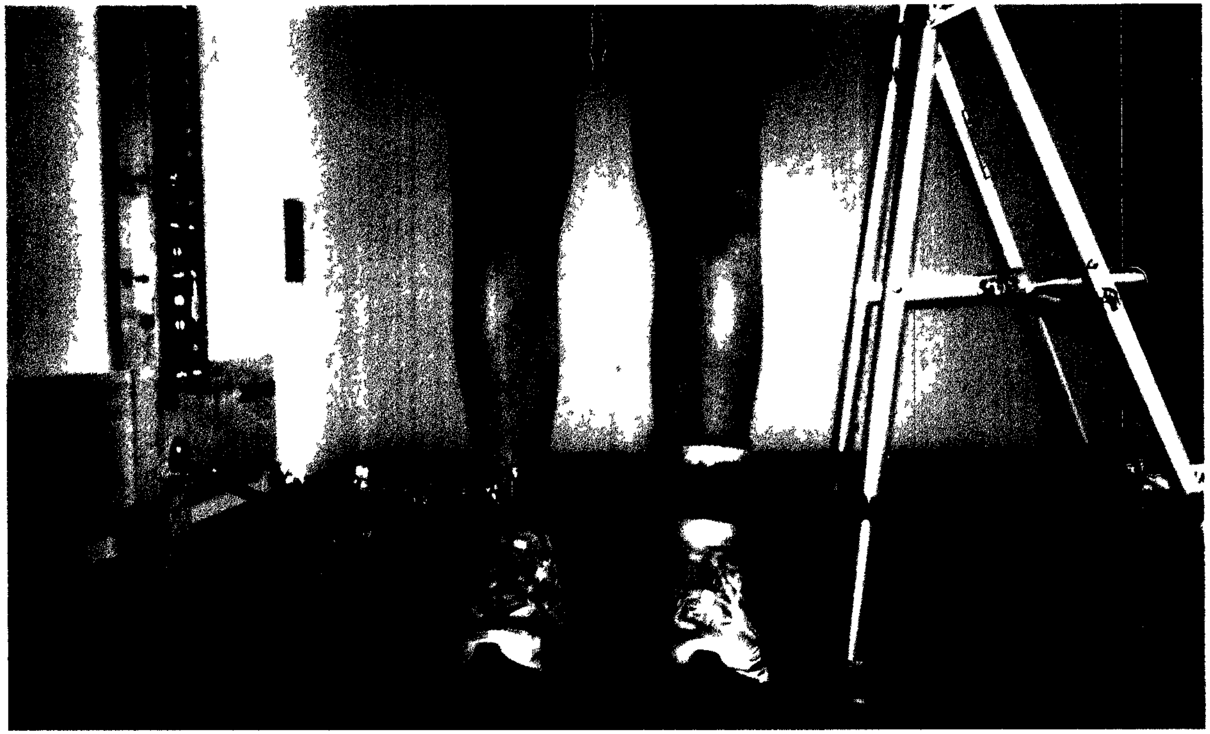
		Mode (Nm)				Mode (Normalized)			
		PFD		Isokinetic		PFD		Isokinetic	
Muscle Group	Gender	*mean*	*±sd*	*mean*	*±sd*	*mean*	*±sd*	*mean*	*±sd*
Hip Abductors	M	139.80	31.29	68.79	22.40	9.19	2.15	4.49	1.33
	F	79.69	28.58	50.49	10.30	8.15	2.83	5.24	1.35
	T	109.75	42.44	59.64	19.36	8.67	2.49	4.87	1.35
Hip Internal Rotators	M	65.50	15.01	57.14	19.95	4.24	0.57	3.78	1.47
	F	40.31	13.82	33.01	9.81	4.13	1.52	3.42	1.15
	T	52.91	19.07	45.08	19.67	4.19	1.11	3.60	1.29
Hip External Rotators	M	73.55	15.89	58.56	20.02	4.18	0.93	3.83	1.25
	F	34.77	8.04	29.67	5.46	3.57	0.79	3.07	0.68
	T	54.16	23.40	44.12	20.58	4.19	1.05	3.45	1.05

Appendix VIII – Table 3.2. Correlation between Isokinetic at 60°/s and PFD PT

	Peak Torque			
	Absolute [Nm]		Normalized	
Muscle Group	*r*	r^2	*r*	r^2
Hip Extensors	0.77‡	0.60	0.42	0.17
Hip Flexors	0.80‡	0.64	0.52*	0.27
Hip Adductors	0.82‡	0.67	0.68†	0.46
Hip Abductors	0.69†	0.48	0.50*	0.25
Hip Internal Rotators	0.60*	0.36	0.24	0.06
Hip External Rotators	0.87‡	0.75	0.68†	0.46

*$p \leq 0.05$; † $p \leq 0.01$; ‡ $p \leq 0.001$

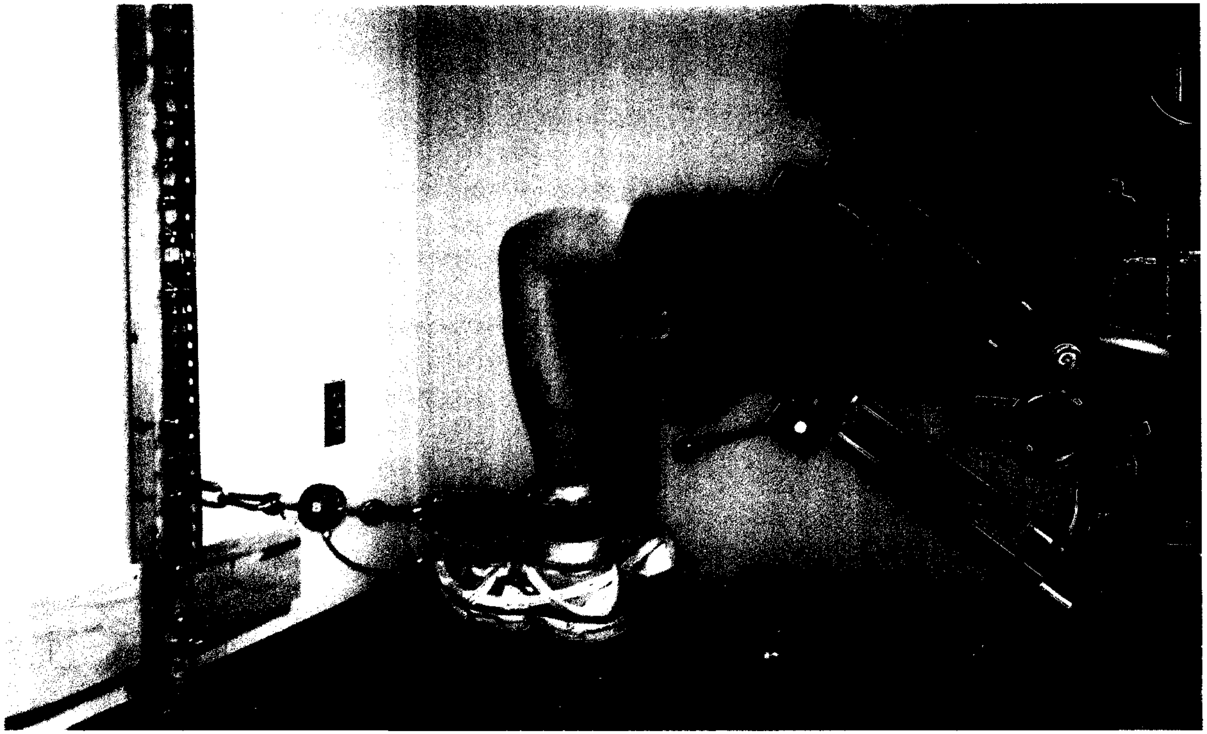
Appendix IX Figure 4.1 Standing Hip Abduction Strength Protocol



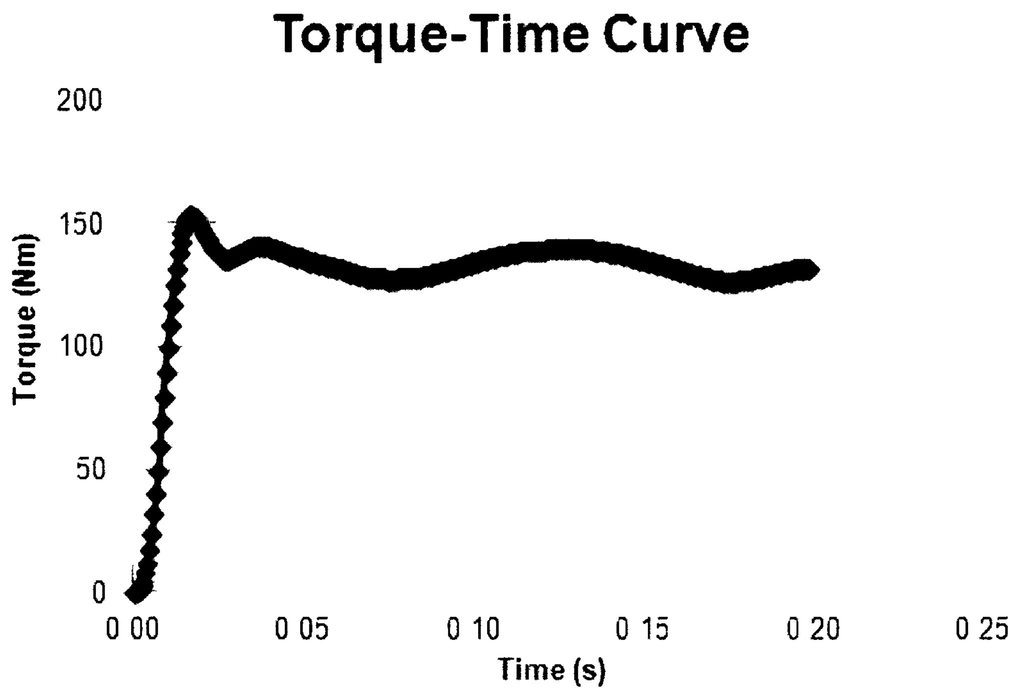
Appendix X Figure 4.2 Standing Hip Extension Strength Protocol

Appendix XI Figure 4.3 Seated Hip Internal Rotation Strength Protocol

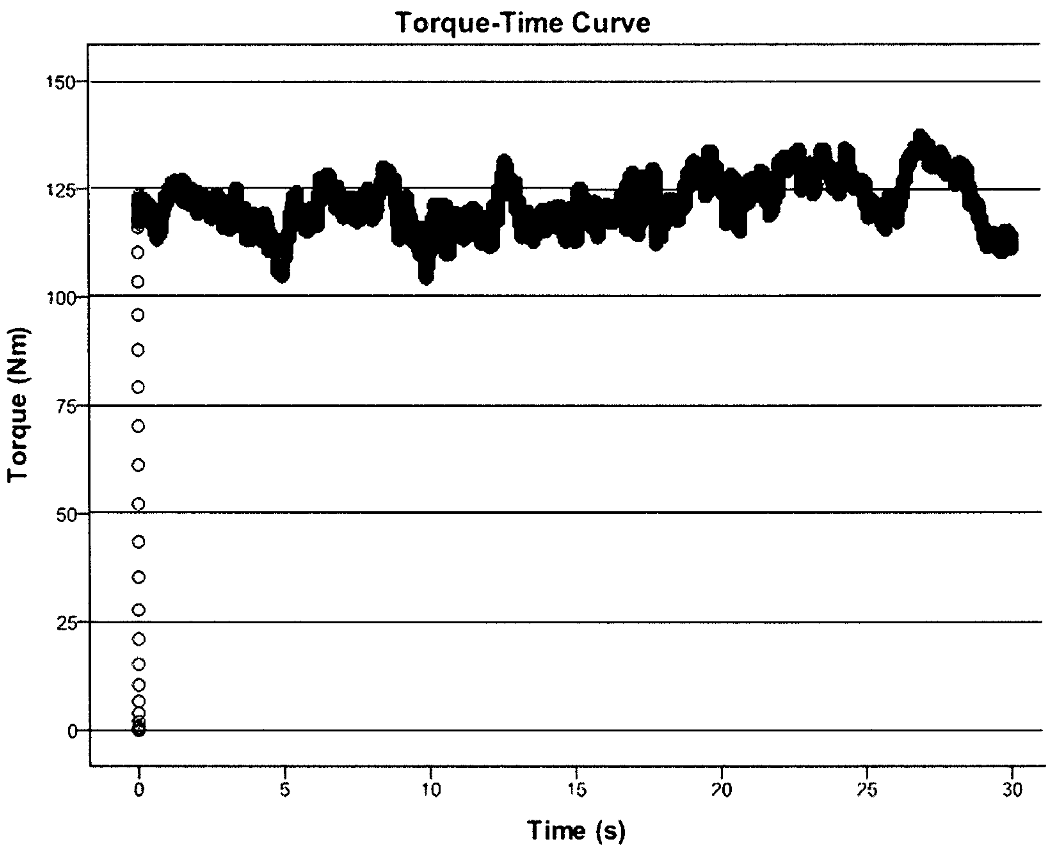
Appendix XII Figure 4.4 Seated Knee Flexion Strength Protocol



Appendix XIII Figure 4.5 Torque-Time Curve Isometric RTD



Appendix XIV Figure 4.6 Torque-Time Curve Isometric Strength Endurance



Appendix XV Table 4.1 Absolute PT, RTD, and Strength (SE) Means and Standard Deviations

				Absolute RTD (Nm/s)									
		Absolute PT (Nm)		0-30 ms		0-50 ms		0-100 ms		0-200 ms		SE (FI)	
Measure	Sex	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
AB	M	162.88	37.52	4499.25	1110.59	2748.26	692.05	1375.86	345.17	689.79	178.16	27.50	4.63
	F	113.93	31.22	3060.09	961.41	1860.89	584.10	931.41	289.83	461.11	143.59	29.70	7.27
AD	M	168.44	47.93	4480.90	1341.39	2746.61	827.30	1375.11	409.76	687.89	211.51	27.15	9.16
	F	110.43	26.20	2885.53	864.00	1760.57	531.02	891.24	266.58	451.71	140.88	22.38	8.33
HE	M	161.27	51.46	4183.46	1528.84	2540.35	927.33	1284.54	473.02	645.01	244.99	33.46	8.57
	F	102.79	35.97	2432.21	1037.53	1476.32	627.60	738.67	299.48	373.51	142.70	33.50	9.99
HF	M	157.30	39.34	4054.97	1058.25	2453.49	654.72	1230.41	320.51	624.42	167.40	30.49	8.31
	F	112.12	30.15	2859.05	983.94	1740.70	604.30	879.93	299.57	440.28	141.08	27.15	8.66
KE	M	220.02	58.87	5737.57	1454.57	3487.83	892.75	1768.59	457.21	887.65	236.40	24.45	11.98
	F	137.60	30.44	3590.68	849.01	2183.51	523.54	1094.00	265.25	548.33	134.63	23.81	11.33
KF	M	132.71	41.37	3466.81	1206.59	2110.28	736.48	1059.84	369.69	533.03	183.34	30.38	9.34
	F	94.38	25.95	2413.73	736.58	1464.87	449.16	733.52	224.10	366.54	112.60	25.79	10.94
ER	M	70.01	21.80	1696.36	632.24	1029.78	383.77	511.10	192.42	256.04	96.80	34.97	8.36
	F	47.16	10.21	1059.90	298.53	634.36	181.79	317.12	94.73	158.57	49.25	33.15	8.25
IR	M	66.32	18.35	1564.29	539.11	950.33	332.45	481.43	169.21	243.49	86.29	24.79	10.63
	F	49.23	15.84	1105.61	474.65	670.73	293.74	340.31	152.62	168.97	73.73	25.08	10.77

Note. Nm = Newton·meters; M = males; F = females; FI = Fatigue Index Ratio; s = seconds; ms = milliseconds

Appendix XVI Table 4.2 Normalized PT and RTD Means and Standard Deviations

				Normalized RTD							
		Normalized PT		0-30 ms		0-50 ms		0-100 ms		0-200 ms	
Measure	Sex	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
AB	M	11 88	2 83	3 28	83	2 00	51	1 00	26	50	14
	F	10 15	2 14	2 72	68	1 66	41	83	21	41	11
AD	M	12 27	3 44	3 27	1 01	2 00	62	1 01	32	50	16
	F	9 98	2 42	2 61	77	1 59	47	80	24	41	12
HE	M	11 80	3 79	3 04	1 10	1 85	67	93	34	47	17
	F	9 09	2 05	2 16	64	1 31	38	66	19	33	09
HF	M	11 55	3 09	2 96	70	1 78	41	90	21	45	10
	F	10 02	2 27	2 56	79	1 56	48	79	24	39	11
KE	M	16 23	4 84	4 25	1 33	2 59	82	1 31	41	66	20
	F	12 49	3 09	3 26	85	1 98	52	99	26	50	13
KF	M	9 75	3 14	2 54	93	1 55	57	78	28	39	14
	F	8 46	2 15	2 17	63	1 32	38	66	19	33	10
ER	M	5 17	1 87	1 25	51	76	31	38	15	19	08
	F	4 26	1 01	95	27	57	16	29	08	14	04
IR	M	4 89	1 59	1 15	45	70	28	36	14	18	07
	F	4 42	1 33	99	39	60	24	30	12	15	06

Appendix XVII Table 4.3 Association of Absolute PT, RTD, and Endurance Strength

	Absolute PT		Absolute RTD							
			0-30 ms		0-50 ms		0-100 ms		0-200 ms	
	r	r^2	*r*	r^2	*r*	r^2	*r*	r^2	*r*	r^2
AB PT	-	-	.984	.968	.983	.965	.982	.964	.975	.951
AB SE	.150	.022	.120	.014	.117	.014	.129	.017	.119	.014
AD PT	-	-	.967	.935	.966	.933	.969	.939	.968	.937
AD SE	.304	.092	.322	.104	.320	.103	.333	.111	.315	.099
HE PT	-	-	.954	.910	.953	.908	.953	.909	.957	.916
HE SE	.125	.016	.145	.021	.138	.019	.137	.019	.143	.020
HF PT	-	-	.941	.885	.938	.880	.939	.881	.949	.901
HF SE	.206	.043	.215	.046	.198	.039	.187	.035	.203	.041
KE PT	-	-	.945	.894	.942	.887	.949	.901	.956	.914
KE SE	.024	.001	.055	.003	.055	.003	.056	.003	.045	.002
KF PT	-	-	.986	.972	.985	.971	.985	.970	.985	.969
KF SE	.340	.115	.344	.118	.339	.115	.342	.117	.334	.112
ER PT	-	-	.983	.966	.982	.965	.972	.945	.966	.933
ER SE	.313	.098	.306	.093	.315	.099	.306	.093	.303	.092
IR PT	-	-	.975	.951	.976	.952	.975	.951	.977	.955
IR SE	.082	.007	.073	.005	.071	.005	.070	.005	.076	.006

Note. r=.311-.388, $p \le 0.05$; r=.389-.470, $p \le 0.01$; $r \ge .471$ $p \le 0.001$; *SE = strength endurance; the correlation coefficients represent the relationship between any two strength parameters within the same muscle group (e.g. relationship between AB PT & AB SE)*

Appendix XVII Table 4.4 Association of Normalized PT, RTD, and Endurance Strength

	Normalized PT		Normalized RTD 0-30 ms		Normalized RTD 0-50 ms		Normalized RTD 0-100 ms		Normalized RTD 0-200 ms	
	r	r^2	r	r^2	r	r^2	r	r^2	r	r^2
AB NPT	-	-	.971	.943	.969	.938	.970	.942	.963	.927
AB SE	.295	.087	.231	.053	.226	.051	.243	.059	.220	.048
AD NPT	-	-	.965	.931	.963	.927	.969	.939	.967	.935
AD SE	.341	.116	.347	.120	.346	.120	.356	.127	.340	.116
HE NPT	-	-	.918	.843	.918	.843	.917	.841	.920	.846
HE SE	.221	.049	.258	.066	.251	.063	.252	.063	.262	.068
HF NPT	-	-	.899	.808	.881	.777	.893	.798	.897	.804
HF SE	.301	.091	.327	.107	.311	.096	.298	.089	.324	.105
KE NPT	-	-	.955	.912	.952	.907	.956	.915	.959	.919
KE SE	.218	.047	.233	.054	.232	.054	.235	.055	.225	.051
KF NPT	-	-	.987	.974	.986	.973	.988	.976	.986	.972
KF SE	.460	.212	.448	.201	.446	.199	.448	.201	.436	.190
ER NPT	-	-	.970	.940	.969	.938	.954	.911	.940	.884
ER SE	.320	.102	.328	.108	.336	.113	.335	.113	.333	.111
IR NPT	-	-	.970	.940	.968	.937	.963	.927	.964	.929
IR SE	.232	.054	.210	.044	.207	.043	.208	.043	.205	.042

Note. r=.311-.388, $p \leq 0.05$; r=.389-.470, $p \leq 0.01$; $r \geq .471 p \leq 0.001$; *SE = strength endurance; the correlation coefficients represent the relationship between any two strength parameters within the same muscle group (e.g. relationship between AB PT & AB SE)*

Appendix XIX Table 5.1 Means and SD for FPT

Measures of Functional Performance	Sex	*M*	*SD*
Single leg Vertical Jump [cm]	M	38 61	6 94
	F	29 88	7 14
Single leg Vertical Jump Work [J]	M	306 56	67 95
	F	200 27	61 42
Crossover Hop for Distance RM [cm]	M	455 98	104 42
	F	330 02	95 17
Crossover Hop for Distance FM [cm]	M	486 63	104 46
	F	358 31	95 72
Triple Hop for Distance RM [cm]	M	518 27	94 82
	F	386 97	86 71
Triple Hop for Distance RM Work [J]	M	4123 79	855 12
	F	2589 83	779 40
Triple Hop for Distance FM [cm]	M	541 15	85 78
	F	417 81	88 50
Triple Hop for Distance FM Work [J]	M	4312 29	852 21
	F	2795 16	811 88
Single Hop for Distance RM [cm]	M	140 60	25 07
	F	105 98	25 73
Single Hop for Distance RM Work [J]	M	1123 73	244 25
	F	700 48	185 25
Single Hop for Distance FM [cm]	M	171 48	25 56
	F	132 70	24 21
Single Hop for Distance FM Work [J]	M	1371 16	276 13
	F	882 20	208 17
30 s Lateral hop Test for Endurance [reps]	M	76 33	9 46
	F	69 66	13 02

Note. cm = centimeters hopped; J = joules; RM = rear foot measures, FM = forefoot measure

Appendix XX Table 5.2 Association of FPT to Absolute and Normalized PT

	Absolute PT								Normalized PT							
MFP	AB	AD	HE	HF	KE	KF	ER	IR	AB	AD	HE	HF	KE	KF	ER	IR
SVJ [cm]	.424	.516	.358	.514	.595	.600	.523	.460	.353	.444	.325	.430	.493	.515	.391	.318
SVJ [J]	.687	.707	.580	.687	.724	.714	.668	.597	.205	.267	.225	.199	.268	.266	.183	.104
CHD RM [cm]	.470	.548	.417	.567	.584	.524	.450	.389	.379	.462	.376	.467	.472	.424	.306	.222
CHD FM [cm]	.474	.551	.423	.571	.586	.526	.452	.394	.377	.460	.376	.465	.469	.421	.303	.221
THD RM [cm]	.545	.631	.526	.608	.603	.549	.584	.471	.443	.539	.479	.486	.469	.431	.427	.302
THD RM [J]	.774	.774	.706	.747	.703	.647	.687	.587	.258	.313	.330	.224	.227	.176	.185	.069
THD FM [cm]	.566	.652	.515	.638	.653	.593	.613	.490	.470	.565	.466	.523	.518	.478	.455	.322
THD FM [J]	.792	.784	.701	.763	.734	.676	.704	.599	.251	.302	.300	.218	.235	.183	.179	.060
SLHD RM [cm]	.477	.592	.410	.579	.569	.457	.495	.407	.422	.538	.392	.519	.467	.369	.364	.278
SLHD RM [J]	.720	.758	.611	.728	.698	.590	.641	.546	.266	.346	.283	.273	.260	.161	.173	.076
SLHD FM [cm]	.536	.639	.470	.614	.608	.513	.551	.455	.430	.537	.421	.489	.459	.384	.377	.278
SLHD FM [J]	.760	.772	.652	.739	.702	.614	.661	.569	.232	.296	.269	.207	.207	.128	.139	.041
30-LHE	.284	.432	.260	.402	.400	.437	.288	.381	.370	.507	.351	.487	.423	.502	.303	.373

Note. r=.311-.388, $p \leq 0.05$; r=.389-.470, $p \leq 0.01$; $r \geq .471 p \leq 0.001$; *SE = strength endurance; MFP=Measures of Function Performance; NRTD= normalized rate of torque development; RM=rear foot measure; FM=forefoot measure; J=joules; cm=centimeters*

Appendix XXI Table 5.3 Association of FPT to AB PT, RTD, and Endurance Strength

		RTD Time Intervals [ms]					NRTD Time Intervals [ms]				
MFP	PT	0-30	0-50	0-100	0-200	NPT	0-30	0-50	0-100	0-200	SE
SVJ [cm]	424	434	436	408	402	353	375	377	342	338	031
SVJ [J]	687	679	678	660	646	205	244	248	220	218	- 055
CHD RM [cm]	470	468	475	455	458	379	397	407	378	381	- 043
CHD FM [cm]	474	472	478	459	462	377	395	405	376	379	- 044
THD RM [cm]	545	544	550	534	528	443	463	474	450	444	021
THD RM [J]	774	754	755	746	733	258	291	300	281	279	- 044
THD FM [cm]	566	565	569	550	541	470	491	499	472	461	050
THD FM [J]	792	771	770	760	744	251	286	293	272	268	- 031
SLHD RM [cm]	477	476	482	478	481	422	440	450	439	437	026
SLHD RM [J]	720	701	702	702	699	266	296	304	295	299	- 039
SLHD FM [cm]	536	532	539	535	539	430	449	460	450	451	049
SLHD FM [J]	760	737	738	739	734	232	264	273	265	271	- 033
30-LHE	284	273	280	270	275	370	359	367	353	353	001

Note. *r=.311-.388, $p \le 0.05$; r=.389-.470, $p \le 0.01$; $r \ge .471 p \le 0.001$; SE = strength endurance; MFP=Measures of Function Performance; NRTD= normalized rate of torque development; RM=rear foot measure; FM=forefoot measure; J=joules; cm=centimeters*

Appendix XXII Table 5.4 Association of FPT to AD PT, RTD, and Endurance Strength

		RTD Time Intervals [ms]					NRTD Time Intervals [ms]				
MFP	PT	0-30	0-50	0-100	0-200	NPT	0-30	0-50	0-100	0-200	SE
SVJ [cm]	516	462	468	471	485	444	390	399	399	421	241
SVJ [J]	707	627	632	629	642	267	221	230	222	246	217
CHD RM [cm]	548	503	501	523	526	462	396	397	414	424	239
CHD FM [cm]	551	507	504	527	529	460	395	396	413	423	239
THD RM [cm]	631	580	574	593	594	539	476	475	486	493	286
THD RM [J]	774	705	702	711	713	313	269	272	271	284	231
THD FM [cm]	652	584	579	603	601	565	484	484	501	507	313
THD FM [J]	784	703	701	713	712	302	248	252	253	266	240
SLHD RM [cm]	592	552	552	562	555	538	483	487	491	493	240
SLHD RM [J]	758	696	698	700	695	346	304	311	304	313	220
SLHD FM [cm]	639	600	600	611	604	537	488	493	498	499	289
SLHD FM [J]	772	711	713	715	710	296	263	270	263	272	233
30-LHE	432	454	448	454	444	507	517	513	517	510	229

Note. r=.311-.388, $p\leq0.05$; r=.389-.470, $p\leq0.01$; $r\geq.471 p\leq0.001$; *SE = strength endurance; MFP=Measures of Function Performance; NRTD= normalized rate of torque development; RM=rear foot measure; FM=forefoot measure; J=joules; cm=centimeters*

Appendix XXIII Table 5.5 Association of FPT to HE PT, RTD, and Endurance

		RTD Time Intervals [ms]					NRTD Time Intervals [ms]				
MFP	PT	0-30	0-50	0-100	0-200	NPT	0-30	0-50	0-100	0-200	SE
SVJ [cm]	358	287	290	288	288	325	253	255	250	248	- 020
SVJ [J]	580	520	522	520	532	225	216	217	215	229	- 048
CHD RM [cm]	417	345	348	358	358	376	309	309	320	322	008
CHD FM [cm]	423	349	353	362	362	376	309	310	321	323	010
THD RM [cm]	526	449	453	455	451	479	412	416	418	414	120
THD RM [J]	706	640	643	644	651	330	322	324	327	339	058
THD FM [cm]	515	434	438	440	440	466	395	399	401	402	147
THD FM [J]	701	634	637	637	647	300	295	296	299	316	070
SLHD RM [cm]	410	353	361	376	380	392	346	357	370	374	100
SLHD RM [J]	611	556	561	574	587	283	284	290	304	321	037
SLHD FM [cm]	470	416	422	439	441	421	387	394	411	413	141
SLHD FM [J]	652	602	606	618	630	269	285	288	303	320	051
30-LHE	260	223	223	222	218	351	318	317	309	304	081

Note. r=.311-.388, p≤0.05; r=.389-.470, p≤0.01; r≥.471p≤0.001; SE = strength endurance; MFP=Measures of Function Performance; NRTD= normalized rate of torque development; RM=rear foot measure; FM=forefoot measure; J=joules; cm=centimeters

Appendix XXIV Table 5.6 Association of FPT to HF PT, RTD, and Endurance Strength

		RTD Time Intervals [ms]					NRTD Time Intervals [ms]				
MFP	PT	0-30	0-50	0-100	0-200	NPT	0-30	0-50	0-100	0-200	SE
SVJ [cm]	514	462	454	441	438	430	391	385	365	359	078
SVJ [J]	687	645	646	639	641	199	202	208	189	195	031
CHD RM [cm]	567	497	491	491	507	467	424	428	420	439	055
CHD FM [cm]	571	500	494	494	510	465	420	425	417	436	056
THD RM [cm]	608	493	493	499	523	486	383	389	394	422	127
THD RM [J]	747	661	666	673	693	224	181	194	192	221	070
THD FM [cm]	638	517	515	519	543	523	416	420	421	450	191
THD FM [J]	763	677	681	687	706	218	178	190	185	213	104
SLHD RM [cm]	579	507	509	507	516	519	470	484	478	482	254
SLHD RM [J]	728	664	670	672	686	273	260	277	268	284	163
SLHD FM [cm]	614	534	532	532	548	489	435	440	437	452	254
SLHD FM [J]	739	677	681	684	700	207	198	210	203	224	144
30-LHE	402	412	401	388	388	487	520	518	495	493	141

Note. r=.311-.388, p≤0.05; r=.389-.470, p≤0.01; r≥.471p≤0.001; SE = strength endurance; MFP=Measures of Function Performance; NRTD= normalized rate of torque development; RM=rear foot measure; FM=forefoot measure; J=joules; cm=centimeters

Appendix XXV Table 5.7 Association of FPT to KE PT, RTD, and Endurance Strength

		RTD Time Intervals [ms]					NRTD Time Intervals [ms]				
MFP	PT	0-30	0-50	0-100	0-200	NPT	0-30	0-50	0-100	0-200	SE
SVJ [cm]	595	541	538	542	552	493	427	425	439	461	- 079
SVJ [J]	724	642	636	645	656	268	188	185	206	230	- 213
CHD RM [cm]	584	600	601	601	598	472	450	452	467	480	042
CHD FM [cm]	586	602	604	603	601	469	447	450	464	477	041
THD RM [cm]	603	586	582	582	584	469	421	417	430	444	151
THD RM [J]	703	666	660	665	668	227	174	171	190	206	- 038
THD FM [cm]	653	635	632	638	637	518	472	470	489	503	146
THD FM [J]	734	692	686	696	697	235	181	179	203	219	- 060
SLHD RM [cm]	569	573	572	584	589	467	443	442	466	486	117
SLHD RM [J]	698	675	670	684	691	260	222	221	248	270	- 051
SLHD FM [cm]	608	620	619	629	633	459	445	447	468	487	143
SLHD FM [J]	702	680	676	689	694	207	175	175	200	220	- 060
30-LHE	400	450	452	449	452	423	453	455	462	475	- 026

Note. r=.311-.388, $p \le 0.05$; r=.389-.470, $p \le 0.01$; $r \ge .471$ $p \le 0.001$; *SE = strength endurance; MFP=Measures of Function Performance; NRTD= normalized rate of torque development; RM=rear foot measure; FM=forefoot measure; J=joules; cm=centimeters*

Appendix XXVI Table 5.8 Association of FPT to KF PT, RTD, and Endurance Strength

		RTD Time Intervals [ms]					NRTD Time Intervals [ms]				
MFP	PT	0-30	0-50	0-100	0-200	NPT	0-30	0-50	0-100	0-200	SE
SVJ [cm]	.600	.608	.609	.615	.614	.515	.514	.518	.525	.525	.119
SVJ [J]	.714	.686	.688	.687	.690	.266	.282	.287	.288	.292	.046
CHD RM [cm]	.524	.558	.559	.562	.566	.424	.457	.460	.462	.462	.042
CHD FM [cm]	.526	.560	.561	.564	.568	.421	.454	.457	.460	.460	.044
THD RM [cm]	.549	.574	.574	.579	.585	.431	.463	.465	.471	.473	.143
THD RM [J]	.647	.629	.630	.630	.639	.176	.213	.216	.218	.224	.058
THD FM [cm]	.593	.614	.614	.619	.626	.478	.505	.506	.512	.517	.148
THD FM [J]	.676	.650	.651	.649	.660	.183	.214	.218	.219	.227	.056
SLHD RM [cm]	.457	.497	.496	.500	.505	.369	.412	.412	.416	.419	.103
SLHD RM [J]	.590	.589	.591	.591	.599	.161	.206	.210	.210	.217	.048
SLHD FM [cm]	.513	.550	.549	.553	.558	.384	.429	.430	.433	.437	.142
SLHD FM [J]	.614	.603	.605	.603	.612	.128	.173	.176	.175	.183	.058
30-LHE	.437	.468	.465	.465	.470	.502	.515	.513	.510	.521	.062

Note. r=.311-.388, p≤0.05; r=.389-.470, p≤0.01; r≥.471p≤0.001; SE = strength endurance; MFP=Measures of Function Performance; NRTD= normalized rate of torque development; RM=rear foot measure; FM=forefoot measure; J=joules; cm=centimeters

Appendix XXVII Table 5.9 Association of FPT to ER PT, RTD, and Endurance Strength

		RTD Time Intervals [ms]					NRTD Time Intervals [ms]				
MFP	PT	0-30	0-50	0-100	0-200	NPT	0-30	0-50	0-100	0-200	SE
SVJ [cm]	.523	.503	.505	.483	.485	.391	.415	.418	.400	.413	.046
SVJ [J]	.668	.653	.652	.642	.648	.183	.267	.270	.264	.284	.047
CHD RM [cm]	.450	.414	.420	.405	.396	.306	.310	.321	.303	.309	.110
CHD FM [cm]	.452	.417	.422	.408	.398	.303	.308	.319	.302	.308	.108
THD RM [cm]	.584	.554	.554	.550	.542	.427	.445	.448	.444	.445	.360
THD RM [J]	.687	.671	.669	.673	.671	.185	.269	.274	.279	.289	.247
THD FM [cm]	.613	.587	.585	.581	.567	.455	.477	.479	.474	.474	.288
THD FM [J]	.704	.691	.687	.692	.687	.179	.270	.274	.279	.288	.186
SLHD RM [cm]	.495	.475	.464	.459	.445	.364	.381	.371	.367	.362	.205
SLHD RM [J]	.641	.631	.621	.623	.616	.173	.255	.251	.254	.259	.156
SLHD FM [cm]	.551	.527	.518	.518	.503	.377	.399	.394	.395	.391	.222
SLHD FM [J]	.661	.651	.643	.648	.642	.139	.230	.229	.237	.243	.148
30-LHE	.288	.270	.267	.246	.236	.303	.303	.300	.283	.279	.105

Note. $r=.311-.388$, $p\leq0.05$; $r=.389-.470$, $p\leq0.01$; $r\geq.471 p\leq0.001$; *SE = strength endurance; MFP=Measures of Function Performance; NRTD= normalized rate of torque development; RM=rear foot measure; FM=forefoot measure; J=joules; cm=centimeters*

Appendix XXVIII Table 5.10 Association of FPT to IR PT, RTD, and Endurance Strength

		RTD Time Intervals [ms]					NRTD Time Intervals [ms]				
MFP	PT	0-30	0-50	0-100	0-200	NPT	0-30	0-50	0-100	0-200	SE
SVJ [cm]	460	460	455	465	489	318	356	356	373	391	- 122
SVJ [J]	597	575	572	585	606	104	187	193	216	223	- 194
CHD RM [cm]	389	380	376	379	383	222	250	247	261	261	- 066
CHD FM [cm]	394	384	380	383	387	221	250	247	261	261	- 065
THD RM [cm]	471	432	430	441	440	302	312	312	333	327	146
THD RM [J]	587	537	538	553	554	069	132	140	167	157	007
THD FM [cm]	490	448	450	463	465	322	330	334	357	352	103
THD FM [J]	599	546	550	567	570	060	125	136	164	154	- 033
SLHD RM [cm]	407	354	361	359	374	278	261	269	278	278	031
SLHD RM [J]	546	485	492	496	511	076	117	130	148	144	- 068
SLHD FM [cm]	455	411	418	416	428	278	286	296	305	302	062
SLHD FM [J]	569	515	522	527	539	041	103	117	135	129	- 064
30-LHE	381	367	366	370	380	373	375	373	388	390	029

Note. $r=.311-.388$, $p\leq0.05$; $r=.389-.470$, $p\leq0.01$; $r\geq.471 p\leq0.001$; *SE = strength endurance; MFP=Measures of Function Performance; NRTD= normalized rate of torque development; RM=rear foot measure; FM=forefoot measure; J=joules; cm=centimeters*

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