

Sex differences in triple extensor rate of torque development may explain variance in vertical jump performance

by
Dylan Wile

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Abstract approved: _____

Marc Norcross

Background: While males generally outperform females in athletic tasks, the underlying mechanisms for this difference remain unclear. Explosive neuromuscular performance of the triple extensors, often investigated via rate of torque development (RTD), is crucial for athletic tasks such as a vertical jump. **Purpose:** To assess sex differences in rapid torque development of the triple extensors. **Methods:** 30 participants (15 male and 15 female) were measured for maximal vertical jump height and RTD of the knee extensors, hip extensors, and ankle plantar flexors during an isometric contraction were calculated at two time intervals (onset of torque to 50 and 200 ms after torque onset, respectively). Separate 2 (Sex) x 2 (Time) mixed-model ANOVAs were utilized to examine the influences of sex and contraction phase on explosive torque production. **Results:** Males exhibited greater early and late phase knee ($p < .001$) and ankle ($p = .009$) extensor RTD. Hip RTD from 0-200 ms was greater than hip RTD from 0-50 ms for both sexes ($p < .001$). At the knee, males displayed a greater difference in RTD compared to females during the interval from 0-50 ms than from 0-200 ms ($p < .001$). **Conclusion:** Early RTD is more closely associated with neural drive. As a result, the greater difference in RTD between males and females during KNEE50 compared to KNEE200 indicates that males are likely able to produce greater neural drive to the knee extensors during the early stages of contraction that may in part explain sex differences in vertical jump height. Future training programs should emphasize neural targeted training to optimize performance gains, especially in female athletes.

Key Words: Sex differences, Rate of Torque Development, RTD, Triple Extension, Vertical Jump Height

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I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

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Chapter 1: Introduction

Improving athletic performance is a central goal among many professional and recreational athletes. It is clear that explosive muscular performance is essential for athletic performance (Ramírez-Campillo et al. 2014; Buchheit et al. 2014). While numerous training regimens have been developed in order to enhance neuromuscular factors related to explosive athletic performance, (Taipale et al. 2013; Ramírez-Campillo et al. 2014; Michailidis et al. 2013) the best method of training remains unclear. However, regardless of the specific mode of training, it is generally accepted that triple extensor (i.e. hip extensors, knee extensors, and ankle extensors) function is essential for athletic performance as many explosive movements such as jumping (Michael H Stone 2003), cycling (Watsford et al. 2009) and sprinting (Bračić et al. 2011) require rapid force production from these muscle groups.

It is well established that males exhibit superior explosive athletic performance when compared with their female counterparts in events such as the high jump, long jump, and 100 meter sprint (Thibault et al. 2010). In order to understand the mechanisms behind sex differences in athletic performance, researchers commonly compare sex differences in neuromuscular function (Hannah et al. 2012; Inglis 2013) and maximal muscle strength (Stock et al. 2013; Miller et al. 1993; Colliander and Tesch 1989). Previous investigators suggest sex differences in maximal muscle strength is one possible explanation for differences in explosive athletic performance (Baldon et al. 2012; Michael H Stone 2003; J. R. Blackburn and Morrissey 1998). Baldon et al. (2012) posited that male's superior performance capabilities could be a result of differences in isokinetic peak torque (PT). Although PT has been associated with execution of athletic movements (Anderson et al. 1991; Baldon et al. 2012), athletic tasks typically involve time windows less than 250 ms (Dapena and Chung 1988; Kuitunen, Komi, and Kyröläinen 2002; Luhtanen and Komi 1979). In contrast, it often requires at least 300 ms to achieve PT (Thorstensson et al. 1976a). Therefore, PT may not be the best indicator of athletic muscular function, as athletes do not have sufficient time to achieve PT during explosive, sport-specific

movements. Further, recent research suggests that greater rate of muscle force development may be more closely related to athletic performance (Bračić et al. 2011) given that it more closely aligns with the available time that an athlete has to execute an explosive athletic movement.

Given peak torque's apparent limitations in explaining athletic performance, another performance measure, rate of torque development (RTD), has become a topic of exploration. When comparing RTD and PT measures to explosive athletic performance, RTD appears to be more related to athletic performance, perhaps most when measuring the early time intervals of RTD (Thompson, Eric D. Ryan, et al. 2013; Chang et al. 2015). This is because specific time intervals likely allude to different, trainable factors influential to athletic performance (Aagaard et al. 2002b). For example, RTD calculated from the onset of torque development to 50 ms after torque onset (RTD50) is commonly assessed (Folland, Buckthorpe, and Hannah 2013; Hannah et al. 2012; Aagaard et al. 2002b) as it describes the time window associated with neural factors such as rate coding, motor unit recruitment, and motor unit synchronization (Aagaard et al. 2002b). RTD calculated from torque onset to 200 ms after torque onset (RTD200) is reported to be associated with muscular factors such as relative composition of type I and type II fibers (Aagaard et al. 2002b). Since both neural (Aagaard et al. 2002b) and muscular structures (Dons et al. 1979) are trainable, and optimizing athletic performance is a common goal, it is important to identify and specifically train factors that highly influence athletic performance.

Given that males tend to exhibit superior athletic performance, and greater RTD of the knee and ankle extensors has been linked to greater vertical jumping performance (Chang et al. 2015), it is plausible that greater triple extensor RTD in males compared to females may help to explain sex differences in athletic performance. When comparing intrinsic muscle fiber characteristics, males tend to display a significantly greater proportion of type II fibers in the vastus lateralis (Miller et al. 1993) which could result in greater RTD. However, examination of recent research indicates that sex differences in RTD, after accounting for anthropometric differences, are equivocal (Hannah et al. 2012; Inglis

2013; Behm and Sale 1994). Some studies have shown significant differences between sexes in RTD (Inglis 2013; Troy Blackburn et al. 2009; Bell and Jacobs 1986) while others have not (Hannah et al. 2012; Behm and Sale 1994). It is important to note that although a recent study observed no significant sex differences in relative RTD (Hannah et al. 2012), the study normalized RTD to maximal voluntary contraction (MVC) rather than to body mass. Normalization to MVC limits utility of data when relating to explosive performance as an individual's jumping performance (acceleration of an individual's center of mass) is predicated on the magnitude of torque produced relative to their mass, rather than the proportion of torque produced relative to their maximum torque production capacity. In fact, Thompson et al. (2013) found a significant relationship between RTD and vertical jump performance only after normalization to body weight. The other publication that did not observe sex differences in relative RTD measured ankle dorsiflexion performance (Behm and Sale 1994) likely because the tibialis anterior is a superficial, and easy muscle to evoke using electrical stimulation. However, the tibialis anterior has no utility in explosive athletic performance. We have yet to see a study that investigates sex differences in early and late phase RTD, normalized to body mass, of each of the triple extensor muscle groups that are highly important for explosive athletic movements such as vertical jumping.

Given the lack of clarity in relative sex differences in RTD, and the importance of measuring RTD at specific time intervals to assess physiologic function, the purpose of this study was to investigate whether there are significant sex or time based differences in isometric hip extension, knee extension, and ankle extension RTD.

Chapter 2: Literature Review

2.1 Athletic Performance:

Given many athletes have a clear interest in optimizing athletic performance, training programs are constantly developed and implemented in attempt to improve athletic performance. Although many of these programs have merits, it remains unclear what physiologic factors are the most influential to athletic performance and how these factors are optimally trained. Researchers have used various methods to quantify athletic performance including participation in elite level competition (Thompson, Eric D. Ryan, et al. 2013), sprint times (Sawyer et al. 2002; Bračić et al. 2011), and vertical jump height (Dapena and Chung 1988; Chang et al. 2015). These researchers then attempt to find the underlying mechanisms that may explain greater athletic performance. Elucidating mechanisms behind differences in performance often includes investigation of both the neural and muscular systems as well as identification and utilization of performance indicators influential to athletic performance (Aagaard et al. 2002b; Inglis 2013; Hannah et al. 2012).

2.2 Sex Differences

One method for investigating performance discrepancy is by comparing two populations that tend to differ in explosive athletic performance. This method allows researchers to exploit the differences in performance and analyze influential factors that may explain the discrepancies in performance. One of the most common methods of finding performance discrepant populations is by comparing sexes (Hannah et al. 2012; Bell and Jacobs 1986; Berger et al. 2012; Inglis 2013) as males consistently exhibit superior athletic performance when compared with their female counterparts (Thibault et al. 2010). Once a physiological factor is identified explaining sex differences in explosive performance, training methods tied to that physiological factor may then be developed to bridge the gap between male's and female's performance capabilities. If successful, the training program may also be utilized for other populations to generally improve athletic performance. Some of the proposed factors in explaining athletic performance include peak torque (PT) (Baldon et al. 2012; Cerrah, Güngör, and Yılmaz 2012), rate of torque development

(RTD) (Aagaard et al. 2002b; Kitagawa 2013; Inglis 2013), and contractile impulse (CI) (S. T. Johnson, Kipp, and Hoffman 2012).

2.3 Triple Extension

When investigating the neuromuscular factors associated with explosive performance, it is important to consider the muscles most influential to a given movement. The triple extensor muscles (i.e. hip extensors, knee extensors, and ankle extensors) are highly relevant in explosive athletic performance as many athletic movements such as jumping (Michael H Stone 2003), cycling (Watsford et al. 2009) and sprinting (Bračić et al. 2011) require rapid force production from these muscles. However, many previous studies that investigate neuromuscular performance have explored only one muscle group (P. Aagaard and Andersen 1998; Aagaard et al. 2002b; Keitaro Kubo, Kanehisa, and Fukunaga 2003; Babault et al. 2003; Frontera et al. 1988; Magnusson et al. 2003). Investigation of neuromuscular performance should incorporate each triple extension muscle group, as each muscle has its own contribution to athletic performance. In accordance, Chang et al. (2015) found that both greater ankle and knee extensor RTD were associated with higher vertical jump height. Dapena and Chung (1988) found that an athlete must extend all three lower limb joints quickly in order to optimally execute a high jump. Given that ground reaction force represents the culmination of triple extensor torque generation, McLellan, Lovell, and Gass' (2011) finding that greater peak and average rates of ground reactions forces were associated with greater vertical jump performance suggest that all three extensor muscle groups influence athletic performance. Although some may argue that based on information from one influential muscle you could postulate about muscular function of other influential muscles, Inglis (2013) suggested that different muscle groups have varying levels of muscle mass and strength. Thus, extrapolating information from how one muscle behaves to other relevant muscles likely leads to inaccuracies. We therefore stress the importance of evaluating each triple extensor muscle individually, as each may have its own role in explaining explosive athletic performance.

2.4 Peak Torque

Within each influential muscle group, certain factors appear relevant when relating to athletic performance. Peak torque (PT), or the maximum amount of torque produced, is commonly assessed as it has been widely associated with athletic performance (Cerrah, Güngör, and Yılmaz 2012; Baldon et al. 2012; Anderson et al. 1991). PT is often measured during an isometric contraction and used as an indicator of maximal strength (Anderson et al. 1991; Herda et al. 2008). Males tend to demonstrate greater absolute peak torque values than females (Hannah et al. 2012; Stock et al. 2013; Pincivero et al. 2001). While it has been suggested that the majority of sex related differences in PT can be attributed to differences in body mass (Seger and Thorstensson 1994; Colliander and Tesch 1989); when PT is normalized to body weight, males continue to display increased PT values (Colliander and Tesch 1989; Berger et al. 2012). A variety of factors including muscle cross sectional area, fascicle length, muscle fiber distribution, and neural drive may explain why sex differences exist in muscular strength, and possibly why sex differences exist in athletic performance.

2.4a: Physiological Cross Sectional Area

CSA has been suggested to be a major indicator of force production (Fukunaga et al. 2001; Ikai and Fukunaga 1968; Miller et al. 1993) and more specifically maximum torque production (Ikai and Fukunaga 1968; Schantz et al. 1983). This suggestion is logical as larger CSA is associated with increased width of individual muscle cells and increased availability of contractile proteins (Russell, Motlagh, and Ashley 2000) resulting in greater torque production (Geisler et al. 2011). Although some researchers have identified a relationship between muscular performance and CSA, this result is not always consistent. Frontera et al. (1988) suggest that the increase in CSA with resistance training was associated with similar gains in strength. Similarly, males and females typically show little to no difference in strength after accounting for differences in CSA (Miller et al. 1993; Maughan, Watson, and Weir 1983; Sale et al. 1987). However, Dons et al. (1979) reported that while strength and CSA did increase with strength training, they did not increase together linearly. Therefore, although it is likely that increased CSA is one factor explaining male's superior relative peak torque capabilities, it is likely not the only factor explaining sex differences in muscle performance.

2.4b: Muscle Fascicle Length

In addition to CSA, muscle fascicle length appears to play a role in muscle strength. This relationship is best observed by the length-tension relationship (Edman and Andersson 1968; Gordon, Huxley, and Julian 1966). The length-tension relationship posits that in isolated muscle fibers, there are torque declines at short and long fiber lengths due to actin and myosin interactions outside of the optimal range of overlap (Edman and Andersson 1968). More recent research with regards to fascicle length shows higher neural discharge rates with shortened fascicle length (Pasquet, Carpentier, and Duchateau 2005; Babault et al. 2003). More literature has elaborated on specific joints and their optimum joint angles with relation to peak torque (Mayer et al. 1994; Jeter 2013). Although awareness of optimal joint angles for achieving maximum strength may seem influential to athletic performance, it is likely limited in explaining discrepancies in athletic performance, as athletic movements are not performed at fixed joint positions. With regards to sex differences in muscle performance, there is no literature that we are aware of investigating sex related differences in how muscles behave at different lengths. However, given the standardization of joint angles when assessing muscle performance across sexes, it is unlikely that minute differences between sexes in optimal joint angle are the reason for large discrepancies between muscle strength, and potentially explosive athletic performance.

2.4c: Muscle Fiber-Type Distribution:

Muscular strength is also influenced by muscle fiber-type distribution (Miller et al. 1993). It appears that having a higher ratio of type II fibers leads to increased torque as type II fibers generate more muscle force than their type I counterparts, likely a result of increased area exhibited by type II fibers. This could in part explain male's superior peak torque producing capabilities as males tend to have a higher type II to type I fiber ratio (Sale et al. 1987; Murray et al. 1980). However, the literature remains inconclusive as to what extent fiber type ratio explains differences in peak torque.

2.4d: Neural Factors

In addition to muscle morphological influence on muscular strength, nervous system function also heavily influences muscular performance (Aagaard et al. 2002a; P Aagaard

et al. 2000). Some key central and peripheral nervous system factors include alteration of motorneuron firing frequency, neural innervation, presynaptic inhibition, motorneuron excitability, and central descending motor drive (Aagaard 2003). Westing, Seger, and Thorstensson (1990) showed that eccentric force was increased with superimposed electrical stimulation when added to a maximum voluntary contraction (Westing, Seger, and Thorstensson 1990) meaning that additional neural input could increase force production. Another study showed significant decreases in neural inhibition as a result of a training regimen (Aagaard et al. 2000). This decrease in neural inhibition occurred simultaneously with increases in eccentric torque production, which supports the idea that neural factors play a significant role in muscular strength output. Finally, S. T. Johnson, Kipp, and Hoffman (2012) found that sexes differ in spinal level modulation of neural drive. Specifically males showed greater levels of recurrent inhibition, which likely leads to increased net torque production. Therefore, the possibility nervous system-related factors account for at least a portion of sex differences in torque production appears logical.

2.4e: Utility of PT

Although PT has been investigated in the past as a means of understanding muscle performance, recent literature suggests that it is important to consider the time interval over which torque is developed (Bračić et al. 2011; Cronin and Hansen 2005). Athletic activities such as the long jump (110-160 ms) (Luhtanen and Komi 1979); high jump (180-220 ms) (Dapena and Chung 1988); and stance phase of sprinting (80-120 ms) (Kuitunen, Komi, and Kyröläinen 2002) typically require less than 250 ms to complete. However, it often takes 300 ms or more to achieve maximal isometric torque production in the human muscles such as the knee extensors (Thorstensson et al. 1976b). Therefore, PT may be lacking as a muscular indicator of explosive athletic performance as athletes often do not have sufficient time to achieve PT during many athletic movements. In fact, another study concluded that PT measured both at high and low angular velocities had little, if any, relationship with vertical jump performance (Baltrusaitis Genuario and Dolgener 1980). As a result, a less commonly assessed performance indicator, rate of torque development (RTD), has emerged as it takes into account the time window

available to perform athletic movements and may therefore better associate with athletic performance.

2.5 Rate of Torque Development

Rate of torque development (RTD) refers to the change in torque over the change in time as calculated from a torque-time curve (Aagaard et al. 2002a). RTD has been used as a measure in a variety of different studies investigating geriatric functional performance (Crockett et al. 2013), ACL injury (Zebis et al. 2011), and athletic performance (Chang et al. 2015). RTD has also been identified as a direct indicator of the neuromuscular system's ability to develop explosive muscle force (Aagaard et al. 2002b; Baker, Wilson, and Carlyon 1994), and therefore is highly intertwined with explosive athletic movements such as the vertical jump. Given the drive of many athletes to improve athletic performance, researchers have investigated factors influencing RTD with hopes to increase RTD, and ideally explosive athletic performance. Some such factors include force-transmitting structures (Bojsen-Møller et al. 2005), muscular properties, and neural components.

2.5a MTU Stiffness

Musculotendinous (MTU) stiffness refers to the resistance to muscle lengthening and has been associated with the stretch shortening cycle (Wilson, Elliott, and Wood 1992), injury risk (Wilson, Wood, and Elliott 1991; Blackburn, Norcross, and Padua 2011), muscular performance (Wilson, Murphy, and Pryor 1994), and rate of torque development (Bojsen-Møller et al. 2005). One study postulates that MTU stiffness leads to increased muscular performance and rate of torque development due to improved rate of shortening and torque transmission capabilities (Wilson, Murphy, and Pryor 1994). However, the mechanisms to explain these proposed effects are still not perfectly understood. Recent literature has identified an association between RTD and force transmitting structures such as MTU stiffness (Reeves, Maganaris, and Narici 2003; Magnusson et al. 2003). One would expect that given the association between force transmitting structures and RTD, and RTD's influence on athletic performance, that force-transmitting structures would also be correlated with greater athletic performance. However, with reference to maximal jump height, no direct relationship has been

observed (K. Kubo, Kawakami, and Fukunaga 1999). Additionally, when relating MTU stiffness and RTD, it is important to note that force-transmitting structures do not contain contractile components. MTU stiffness may therefore decrease the electromechanical delay (EMD), the time until onset of torque development, as a stiffer unit requires less time to create tension in the muscle. However, it likely will not change the RTD value after onset of torque development.

2.5b Muscular Properties

In addition to force transmitting structures, explosive RTD, similar to PT, is influenced by the intrinsic properties of the muscle. Some examples of intrinsic muscular properties that influence RTD include cross bridge cycling rate (Fitts, McDonald, and Schluter 1991), muscle cross sectional area (Ryan et al. 2011), and fiber-type (relative content of type II myosin heavy chain (MHC) isoforms) (Aagaard et al. 2002b). In fact, a correlation between intrinsic muscle properties and RTD has been shown in the literature (Harridge et al. 1996). Although intrinsic properties of the muscle clearly play a role in RTD, and likely explosive performance, it is also important to consider the central and peripheral nervous control, as it also has a heavy influence on the muscle's ability to rapidly generate force.

2.5c Neural Factors

Neural influence is closely linked to the ability to rapidly develop force (Aagaard et al. 2002b; Häkkinen et al. 1998). Some common neural adaptations thought to lead to increased torque development include increased efferent neural drive and reduced co-activation of antagonist muscle groups. Reduced co-activation of antagonist muscles benefits RTD as inhibiting antagonist muscles reduces the rotational torque working against the agonist muscle group and thus greater net torque may be generated. Greater efferent neural drive, commonly associated with greater rate coding, motor unit recruitment, and motor unit synchronization (Aagaard et al. 2002b), is highly influential to RTD (Aagaard et al. 2002b; Häkkinen et al. 1998). Greater motor unit recruitment leads to faster activation of the motor unit pool, greater synchronization better coordinates muscle action, and greater rate coding leads to more action potentials sent to each motor unit, each logically leads to greater torque production. Nelson (2010) showed

that supramaximal stimulation increases shortening velocity suggesting that greater neural drive leads to increased RTD. In addition, Aagaard et al. (2002) observed parallel gains of efferent drive and RTD in response to a resistance-training program. In fact, of the underlying factors relating to RTD, neural influence seems to be the most influential (Häkkinen et al. 1998; Aagaard et al. 2002b). Häkkinen et al. (1998) found that explosive training elicited significantly more neural adaptations when compared to muscular changes, suggesting that neural adaptations are just as influential, if not more so, as muscular adaptation to greater RTD.

2.5d Time Intervals

As a means of investigating neuromuscular performance, researchers measure RTD at different time intervals to assess which neuromuscular factors are most likely influencing torque production (Chang et al. 2015; Aagaard et al. 2002b). Often, these intervals include both an early and late phase. The early phase of torque development, commonly measured as the time window from onset of torque development to 50 ms after torque onset (RTD50) (Aagaard et al. 2002a; Babault et al. 2003; Thompson, Eric D. Ryan, et al. 2013), is primarily related to neural drive (Aagaard et al. 2002b; Folland, Buckthorpe, and Hannah 2013). The late phase, measured from time of onset to 200 ms after torque onset (RTD200) (Chang et al. 2015), is assessed as a measure of intrinsic muscular properties, as muscular factors tend to influence torque development at times >150 ms (Tillin et al. 2010; Aagaard et al. 2002b; Folland, Buckthorpe, and Hannah 2013). Chang et al. (2015) found that early RTD, specifically from the knee extensors, explained the largest portion of the variance in explosive vertical jump performance. This agrees with previous literature that neural drive is very important for explosive performance (Aagaard et al. 2002b).

2.5e Sex comparisons in RTD

Recent exploration has investigated sex differences in RTD as a means to understand why males tend to exhibit greater explosive athletic performance. Review of recent literature indicates that sex differences in RTD are equivocal after accounting for differences in anthropometric measures. One would expect males to exhibit higher levels of RTD given males perform better athletically, and athletic performance is related to

RTD (Chang et al. 2015). However, while some studies have shown significant differences between sexes in RTD (Inglis 2013; Troy Blackburn et al. 2009; Bell and Jacobs 1986), others have not (Hannah et al. 2012; Behm and Sale 1994). It is important to note that although Hannah et al. (2012) did not observe sex differences in relative RTD, the study normalized to MVC rather than to body mass. Normalization to MVC limits utility of data when relating to explosive performance as an individual's jumping performance (acceleration of an individual's COM) is predicated on the magnitude of torque produced relative to their mass, rather than the magnitude relative to their maximum. In fact, Thompson et al. (2013) suggest that the relationship of RTD to vertical jump performance hinges on normalization to body mass. The other publication that did not observe sex differences in relative RTD measured ankle dorsiflexion performance (Behm and Sale 1994), a muscle group likely less influential in athletic performance. We have yet to see a study that investigates sex differences in RTD normalized to body mass measured at muscle groups highly important for explosive vertical jump performance.

2.6 Focus of Study

Given there is a lack of clarity on why males continue to perform better athletically, and no investigation has examined RTD calculated at different time intervals for each triple extensor muscle, this study aims to investigate whether there are significant differences between sexes performing isometric hip extension, knee extension, and ankle extension on the following muscle performance measures: RTD50 and RTD200.

Chapter 3: Methods

3.1 Experimental Design

A cross-sectional design was utilized in which subjects performed maximum isometric hip, knee, and ankle extension contractions and countermovement vertical jumps.

3.2 Participants

Thirty (15 males and 15 females) participants (Mean \pm SD: Age=23 \pm 2.5 years; Height=172.76 \pm 0.48 cm; and Mass= 72.18 \pm 14.03 kg) were recruited to participate in the study. Participation was voluntary and all subjects provided informed written consent prior to participation. The study protocol was reviewed and approved by the Oregon State University Institutional Review Board. Individuals were eligible to participate if they were recreationally active, defined as engaging in at least 150 minutes of moderate intensity exercise per week (Garber et al. 2011) and reported 1) no history of hip, knee or ankle surgery; 2) no injury or illnesses at the time of testing that limited their ability to be physically active; and 3) no lower extremity or back injury in the 6 months prior to testing. In addition, participants were asked to avoid any strenuous activity on the day of testing prior to reporting to the laboratory.

3.3 Procedures

On the day of testing, subjects were instructed to warm-up for five minutes on a stationary bicycle at light to moderate intensity. Subjects' leg dominance was then assessed as described by Hoffman et al. (1998). In short, patients performed three tests to determine limb dominance. Dominant limb tests included instructing the participant to kick a ball to the assessor, to step up onto a step, and to recover after a posterior perturbation. The dominant limb was defined as the limb used at least twice to kick the ball, step up first, and utilized to regain balance. Finally, height and mass were recorded.

3.4 Vertical Jump

Vertical jump height was measured using a force plate integrated with The MotionMonitor motion-analysis software (Innovative Sports Training, Inc., Chicago,

Illinois). A minimum of three countermovement vertical jumps were performed by each participant in which subjects were instructed to jump as high as possible. Trials were discarded and repeated if the subject's feet did not land fully within the force plate.

3.5 Lower Limb Neuromuscular Performance

Hip extension, knee extension, and ankle extension RTD of the dominant limb were measured using a Biodex System 3 dynamometer (Biodex Medical Systems Inc., Shirley, New York) interfaced with a BIOPAC MP100 Data Collection System (BIOPAC systems Inc., Goleta, California).

3.5a Hip Extension

To measure hip extension, subjects were positioned prone in 30° of hip flexion and 85° of knee flexion with the greater trochanter aligned to the rotational axis of the dynamometer. Subjects' hands were positioned around the underside of the table and a lower back strap was utilized to restrict lumbar back extension. The anterior superior iliac crests were positioned at the edge of the table and a resistance pad placed on the posterior aspect of the distal thigh, just proximal to the knee. Subjects were cued with the instruction, "try to raise the heel to the ceiling" to explain hip extension motion.

3.5b Knee Extension

In knee extensor trials, subjects were seated in the chair reclined back to 70° with the resistance pad placed over the anterior, distal tibia. The knee was positioned in 70° of flexion with the lateral epicondyle in line with the rotational axis of the dynamometer. The subject was then secured to the seat using a strap placed around the waist and instructed to cross the hands over the chest. Subjects were instructed to kick the foot out straight; however, given the relative ease of the motion, few cues were needed to facilitate proper joint motion.

3.5c Ankle Extension

To evaluate ankle extension, subjects were positioned in the same manner as in knee extension trials, except that the knee was positioned in 15° of flexion and the ankle was firmly strapped into 0° of extension with lateral malleolus aligned with the rotational axis

of the dynamometer. The cue used for ankle extension was to “push as if you were pushing a gas pedal”.

3.5d Trial Specifications

For each testing position, subjects were instructed to perform a maximal isometric contraction “as hard and as fast as possible” for three to five seconds in response to a light stimulus. Subjects performed no more than seven trials, averaging four to five, with a 60 second rest interval in between each trial. After each trial, a torque-time curve was produced and displayed on the BioPac software. The curve was inspected to make sure there was a plateau in maximum torque and that no countermovement occurred preceding the onset of contraction. If there was no clear plateau and/or a countermovement was observed, the repetition was discarded and the trial repeated until three successful trials were captured for each joint motion of interest.

3.6 Data Sampling, Processing, and Reduction

The raw voltage signal from the Biodex System 3 dynamometer was sampled at 1000 Hz using a BIOPAC MP100 Data Collection System (BIOPAC systems Inc., Goleta, California). The signal was then digitally low-pass filtered at 10 Hz using a fourth order Butterworth filter and converted to torque (Nm) via a calibration function using custom computer software (LabVIEW, National Instruments Corp., Austin, Texas). RTD was calculated using a line of best-fit curve for the two time intervals of interest. Finally, an anthropometric scaling technique was utilized ($N \cdot m \times kg^{-0.67}$) (Jaric, Mirkov, and Markovic 2005) and the maximum RTD50 and RTD200 values obtained across trials were used for statistical analysis. For vertical jump trials, the vertical component of ground reaction force was sampled at 200 Hz. Flight time was determined using custom computer software and was defined as the time when the vertical ground reaction force equaled zero. Using flight time, initial velocity was calculated, followed by maximum vertical jump height in accordance with Ferreira et al. (2010). The maximum jump height attained during any trial was used for analysis.

3.7 Statistical Analysis:

An independent-samples *t*-test was used to evaluate sex differences in vertical jump height. Separate 2 (Sex) x 2 (Time: RTD50 and RTD200) mixed-model ANOVAs were utilized to evaluate the influences of sex and time on hip, knee, and ankle extensor RTD. In cases where a significant Sex*Time interaction effect was identified, planned pairwise comparisons were performed using Tukey HSD. All statistical analyses were performed using SPSS v21.0 (IBM, INC., Armonk, NY) with statistical significance established a priori ($\alpha \leq 0.05$).

Chapter 4: Results

Vertical Jump Performance:

Anthropometric data was averaged for both males (23.9 ± 2.9 yrs, 180.2 ± 4.4 cm, 78.9 ± 14.0 kg) and females (21.9 ± 1.5 yrs, 165.3 ± 6.8 cm, 65.4 ± 10.7 kg). As shown in Figure 1, males jumped significantly higher than females ($t_{28}=6.25$, $p<.001$).

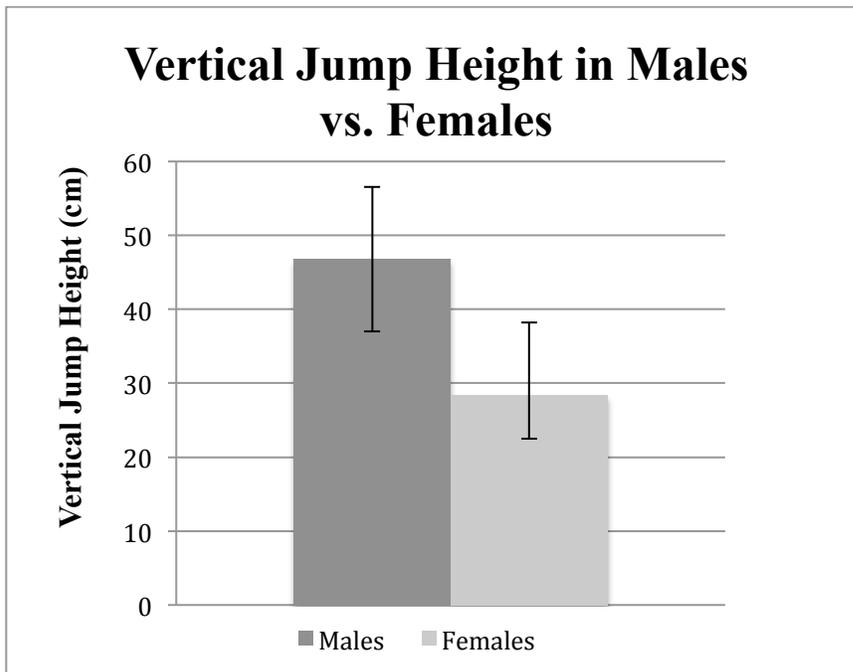


Figure 1. Depicts vertical jump height in both males and females.

Hip Extension RTD

For the hip, there was a significant main effect of time ($F_{1, 28}=47.714$, $p<.001$) with hip extension RTD from onset of torque development to 200ms (HIP200), greater than hip extension RTD from onset of torque development to 50ms (HIP50). However, no significant main effect for sex ($F_{1, 28}=2.971$, $p=0.096$) or significant sex*time interaction effect ($F_{1, 28}=0.063$, $p=0.804$) were identified.

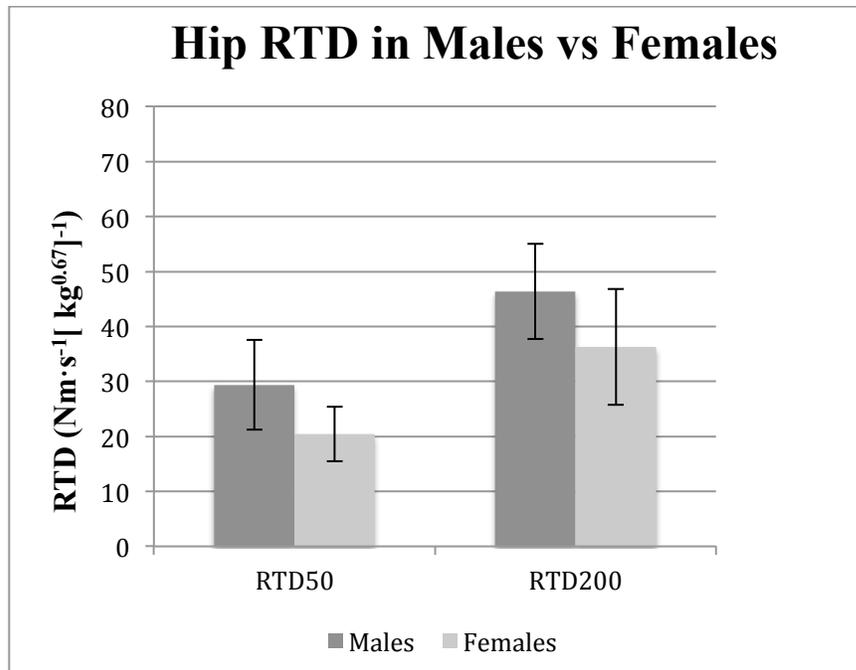


Figure 2. Depicts hip extension RTD in both early and late phase of contraction.

Knee Extension RTD

At the knee, there was a significant main effect for time ($F_{1,28}=22.317, p<.001$) with knee extension RTD from onset of contraction to 50ms (KNEE50) greater than knee extension RTD from onset to 200ms (KNEE200). There was a significant main effect for sex ($F_{1,28}=20.493, p<.001$) showing males produced greater RTD values when compared with females. In addition, an interaction effect was observed with males displaying a greater difference in RTD compared to females during KNEE50 than during KNEE200 ($F_{1,28}=16.833, p<.001$).

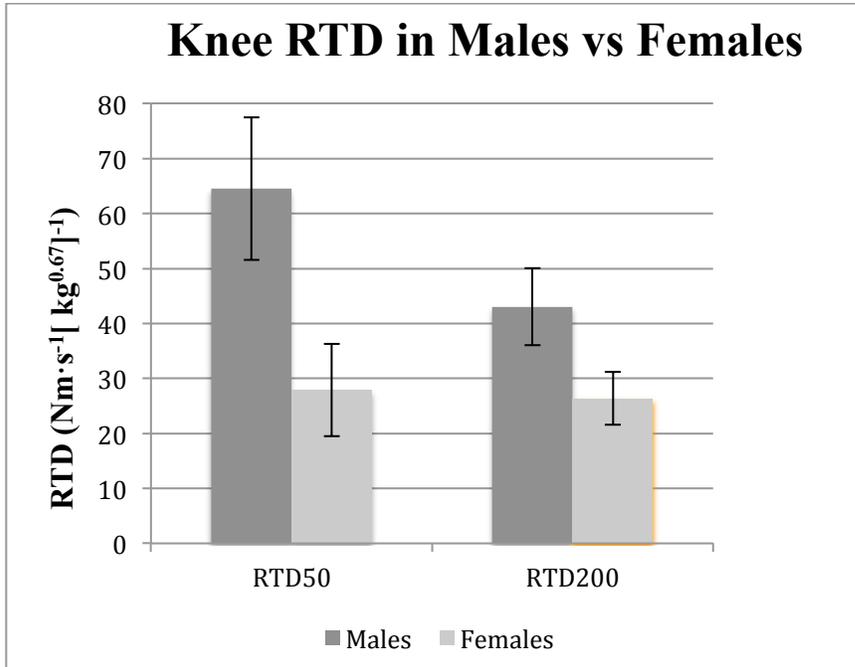


Figure 3. Describes knee extension RTD in both early and late phase of contraction.

Ankle Extension RTD

For the ankle, a significant main effect for sex was observed ($F_{1, 28}=7.781, p=.009$) with males displaying greater RTD compared to females. However, no significant main effect for time ($F_{1, 28}=0.109, p=0.744$), or sex*time interaction effect ($F_{1, 28}=0.423, p=0.521$) was identified.

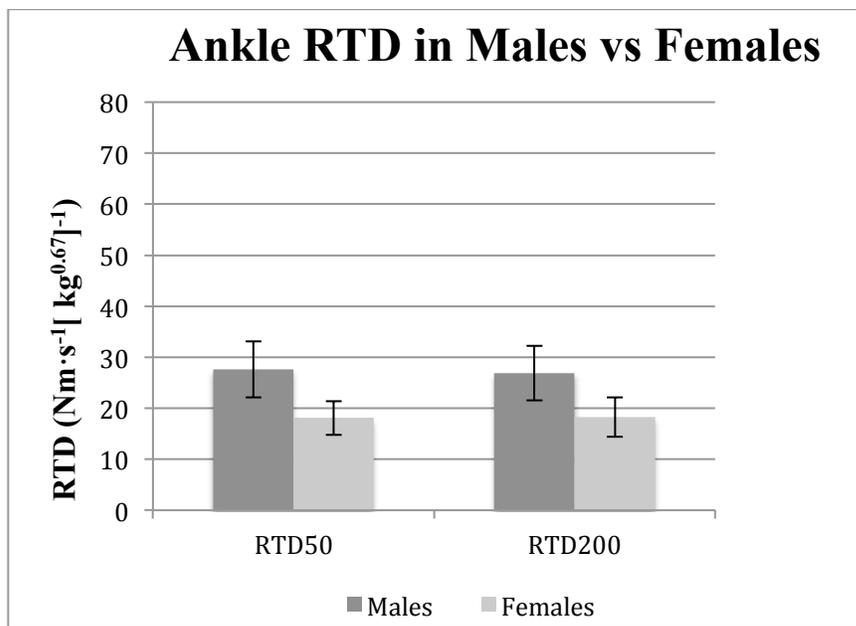


Figure 4. Depicts ankle extension RTD in both early and late phase of contraction.

Chapter 5: Discussion

Primary Findings

The primary findings of this investigation are that males exhibited greater knee and ankle extension RTD during both the early and late phases of contraction (Figure 3 and Figure 4). In addition, there was a trend toward greater hip extension RTD in males across both phases (Figure 2). Interestingly, HIP200 was observed to be greater than HIP50 in both males and females (Figure 2). Finally, an interaction effect was observed at the knee with males displaying a significantly greater difference in RTD compared to females during the early phase (KNEE50) than during the late phase (KNEE200) (Figure 3).

Knee Extension

Consistent with previous findings (Ford et al. 2005; Quatman et al. 2006), males in our study jumped significantly higher during a countermovement vertical jump (Figure 1). An important contributor in vertical jump height is knee extension neuromuscular performance (Nagano, Komura, and Fukashiro 2007; Chang et al. 2015; Hubley and Wells 1983). Hubley and Wells 1983 investigated total positive work contributions of the triple extensors in executing a maximum vertical jump. They found the knee contributed the greatest portion (49%), with the hip (28%) and ankle (23%) each contributing significantly less to total positive work. Chang et al. (2015) showed that when compared to the other triple extensor muscle groups, knee extensor rate of torque development explained the largest percentage of variability in maximum vertical jump height. Finally, Nagano, Komura, and Fukashiro (2007) showed via muscle modeling that in vertical jumping movements, the knee extensors produced nearly twice as much force as other influential muscles in jump height. Resultantly, a large portion of lower limb neuromuscular studies investigate knee extension given its apparent influence in lower limb performance related tasks (Aagaard et al. 2002b; Anderson et al. 1991; Babault et al. 2003; Baltrusaitis Genuario and Dolgener 1980; Croce et al. 1996; Frontera et al. 1988; Hannah et al. 2012). As such, it is logical that males demonstrated greater knee extension RTD across both RTD phases.

We propose that sex differences observed at KNEE50 (Figure 3) may be explained by sex differences in nervous function given that early phase RTD is closely associated with neural drive (Aagaard et al. 2002b; Folland, Buckthorpe, and Hannah 2013). Neural drive depends on the body's ability to increase motor unit recruitment, motor unit synchronization and/or increase rate coding (Aagaard et al. 2002b). Greater motor unit recruitment leads to faster activation of the motor unit pool; greater motor unit synchronization leads to better coordination of muscle response; and greater rate coding results in a greater number of action potentials sent to the motor units. A greater neural drive from a culmination of its derivatives likely leads to more actin and myosin cross bridge cycling within a given time frame and thus faster muscle force and joint torque production.

In addition to sex differences in KNEE50, males also demonstrated greater KNEE200 than females (Figure 3). These results are likely explained by sex differences in muscle fiber characteristics (Aagaard et al. 2002b). Previous literature supports the existence of sex differences in muscle fiber characteristics with males exhibiting a higher type II to type I fiber ratio in the knee extensors (Murray et al. 1980; Simoneau and Bouchard 1989). Additionally, greater type II fiber composition is associated with greater RTD (Harridge et al. 1996), potentially explaining male's greater vertical jump height.

It should be noted that if our data depicted solely a main effect for sex, it would be impossible to conclude which physiologic factor (neural or muscular) explains sex differences in RTD. However, our data shows that the magnitude of sex differences in KNEE50 is greater than the magnitude of sex differences in KNEE200 (Figure 3). Given early RTD is tied with neural function (Aagaard et al. 2002b; Folland, Buckthorpe, and Hannah 2013), it strongly suggests that males have superior neural drive in knee extension during the early phase of isometric torque production. The notion that sex differences exist in knee extensor neural drive is a novel and exciting finding and may have strong ties to sex differences in vertical jump height. However, the notion that sex differences exist in neural function does not stand completely alone in recent scientific literature. Johnson, Kipp, and Hoffman (2012) directly measured neural mechanisms and

showed that sexes differ in modulation of spinal control. Specifically, they found that males showed greater levels of recurrent inhibition, a neural component that may lead to increased extension RTD. In addition, Inglis (2013) showed that when accounting for sex differences in the rate of increase in surface electromyographic activity, differences between sexes in RTD were reduced. This indicates sex differences in neural function likely have in part driven sex differences in RTD. Given our findings and these previous studies, implementation of nervous system targeted training shown to improve neural drive (Aagaard et al. 2002b) in female athletes may decrease the gap between males and females in knee extension RTD and, by extension, vertical jump performance. It should be noted that although we strongly suggest that the sex differences in KNEE50 are a result of variance in neural function, no direct neural measurements were made. Therefore, future study into the direct mechanisms in which sexes differ in knee extension neural drive is warranted to corroborate our findings. In addition, clarification of sex differences in neural function may lead to improved training mechanisms that bridge the gap between sexes in athletic performance tasks.

Ankle Extension

Similar to knee extension RTD, ankle extensor RTD displayed a main effect for sex with males displaying greater RTD (Figure 4). Sex differences in neuromuscular function at the ankle may also explain sex differences in RTD. At the ankle, Holmbäck et al. (2003) found that males display a larger proportional area of type II fibers in the ankle extensors, which may explain males greater ankle extension RTD. The same study also showed that males have greater absolute ankle extensor muscle cross sectional area (Holmbäck et al. 2003). Larger CSA has been associated with increased availability of contractile proteins (Russell, Motlagh, and Ashley 2000) and therefore increased torque production (Geisler et al. 2011). Johnson, Kipp, and Hoffman (2012) identified a significant difference in soleus recurrent inhibition, indicating a definitive difference in ankle extensor neural function exists. However, unlike knee extension, no significant interaction effect was identified at the ankle. Therefore, it is not possible to infer to what extent sex differences in each physiologic factor (CSA, fiber morphology, and neural function) are driving the observed sex differences in ankle extension RTD. Likely, it is a combination of these physiologic factors that fully explains greater ankle extension RTD in males.

Hip Extension

At the hip, although the data did not reach statistical significance, males did display a trend towards greater hip extension RTD ($p=.096$) (Figure 2). A significant main effect of time was also observed at the hip, with HIP200 significantly greater than HIP50 (Figure 2). The observation of HIP200 exceeding HIP50 contrasted the findings at the knee and ankle. This observation is potentially explained by the fiber composition of the hip extensors. M. A. Johnson et al. (1973) showed that when comparing the gluteus maximus with other triple extensors, only the soleus had a lower proportion of type II to type I fibers. Given the gastrocnemius has a large portion of total ankle extensor type II cross sectional area and is therefore responsible for much of the explosive ankle extension torque, it is not surprising that ankle extension RTD did not have a similar late phase spike in RTD as observed in the hip. The relatively low proportion of type II fibers in the gluteus maximus logically explains the greater late phase RTD given type II fibers are responsible for more rapid torque production (Harridge et al. 1996). Therefore, a lack of type II fibers in the gluteus maximus, may further explain slowed torque production.

In addition to fiber type, the architecture, or pennation, of the hip extensors may explain the greater late phase RTD observed at the hip (Kitagawa 2013). The gluteus maximus, unlike any of the other triple extensors, is a multipennate muscle. Although multipennate muscles have a mechanical advantage that allows them to stack more sarcomeres into a given area potentially increasing total force production, their sarcomeres are not aligned in series, likely leading to a slower production of joint torque. Finally, it is plausible the hip extensors may have decreased neural drive when compared with the other triple extensors given the tendency towards greater late phase RTD; however, more study is warranted to investigate this possibility.

Conclusion

It is clear that knee extension neuromuscular performance is important in executing a countermovement vertical jump. The present study found a clear difference in the magnitude of variance between sexes in KNEE50 and KNEE200, which is likely explained by sex differences in neural drive and suggests that sex differences in neural drive during the initial 50 ms of knee extension likely contributes to the greater vertical jump height observed in males. As a result, we suggest that the use of previously described training mechanisms that have been shown to improve knee extension neural drive (Aagaard et al. 2002b) might be implemented to improve athletic performance in females.

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