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Samuel T. Johnson

The ability to quickly generate torque of the triple extensors is critical during rapid movements, especially when there is not enough time to reach peak torque. Rate of torque development (RTD), which is the rate of rise of the torque-time curve, is a commonly used measure of rapid torque generation. However, the relationship between RTD of the triple extensors at different time intervals has yet to be investigated. The purpose of this study was to assess the relationship between RTD of the triple extensors at different time intervals (0-25, 0-50, 0-100, 0-150, 0-200 and 0-250 ms). Thirty healthy, recreationally active volunteers (15 females, 15 males) participated in the study. In order to assess RTD of the triple extensors, isometric hip extension, knee extension, and plantarflexion torque-time curves of the dominant limb were recorded using a Biodex System 3 dynamometer. During the first 50 ms, the correlations were very similar among all three muscle groups. However, after that time period, the relationships between the muscle groups diverged. While relationships of RTD of the KE and plantarflexors (PF) remained consistent across all

the time intervals, relationships of RTD of the hip extensors (HE) and knee extensors (KE) was highest at the 0-50 ms time interval and then lowered at the later time intervals. In addition, relationships of RTD of the HE and PF increased up to the 0-100 ms time interval and then was lower after that time interval. This suggests that the KE and PF exhibited the similar pattern of rapid torque production while the HE exhibited the different pattern of rapid torque production compared to the other two primary triple extensors.

The Relationship between Rate of Torque Development of the Triple Extensors at Different Time Intervals

by
Taichi Kitagawa

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APPROVED:

Major Professor, representing Exercise and Sport Science

Co-Director of the School of Biological and Population Health Sciences

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Dean of the Graduate School

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

Taichi Kitagawa, Author

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CHAPTER 1 – INTRODUCTION

Many athletic performances involve explosive types of movement in which an individual is required to rapidly generate muscle torque within a short period of time for better performance. In order to identify an individual's capability for performance, most traditional measures of muscle torque production have focused primarily on an individual's capability to generate maximal torque (Hicks & McCartney, 1996; Lindeman et al., 1999, and Souza & Powers, 2009). However, the time it takes to reach maximal torque is greater than the time it takes to complete an explosive sporting movement (Luhtanen & Komi, 1979; Dapena & Chung, 1988, and Kuitunen et al., 2002). Therefore, measurements of rapid torque production may be a better functional gauge of muscle torque production.

One commonly used measure of rapid torque production is rate of torque development (RTD), sometimes also called rate of force development. RTD is defined as the slope of the torque-time curve (Aagaard et al., 2002; Andersen & Aagaard, 2006; Morais De Oliveira et al., 2012, and Zebis et al., 2011). The slope is calculated by fitting a line of best fit onto the torque-time curve and measuring the rate of rise of the line. There are several ways to quantify RTD, for example measuring the slope of the torque-time curve from the onset of torque production to peak torque (Holtermann et al., 2007) or the slope of the torque-time curve in different time periods (e.g., 0-30, 0-50, 0-100, and 0-200 ms) (Aagaard et al., 2002). Measuring RTD to peak torque might be evaluated when researchers are interested in determining the rate at which peak torque can be reached. Although this approach may be more beneficial than simply measuring peak torque, it may not capture the time intervals that are more closely associated with explosive types of movement. On the other hand, measuring the slope of the torque-time curve over different time periods allows researchers to detect how rapidly the torque is generated during specific time periods associated with explosive types of movement. Therefore, more recently researchers have been interested in RTD during time intervals that are associated with shorter, more explosive movements (Aagaard et al., 2002, Anderson & Aagaard, 2006, Anderson et al., 2010, Blazevich et al., 2009, Greco et al., 2013, Hannah et al., 2012, Kyrolainen & Komi, 1994, Maffiuletti et al., 2010, Marshall, McEwen, & Robbins, 2011, Morais de Oliveira et al., 2012, Suetta et al., 2004, Thorlund, Aagaard, & Madsen, 2009, and Waugh et al., 2013).

However, one issue with most previous RTD studies is the fact that they have only examined one or possibly two muscle groups. Many explosive activities require individuals to concomitantly perform rapid hip extension, knee extension, and plantarflexion. Collectively, these motions are known as triple extension. The triple extensor muscle groups function in concert to propel the body during explosive movements, such as in jumping, sprinting, or tackling. For instance, an athlete preparing to jump needs to extend all three joints in a short period of time (e.g., less than 220 ms) (Dapena & Chung, 1988). Hence, creating muscle torque rapidly with the triple extensors may be a key for a better performance in most explosive movements. Therefore, it is important to examine RTD of the triple extensors during the time intervals that are associated with the explosive types of movement. Currently, the relationship between RTD of the triple extensors at different time periods is unknown. Therefore, it is important to examine RTD of multiple muscle groups to determine the relationship among RTD of the hip extensors, knee extensors, and plantarflexors during the first 25, 50, 100, 150, 200 and 250 ms from the onset of contraction.

CHAPTER 2 - LITERATURE REVIEW

The Importance of Triple Extension

Many explosive activities require individuals to perform rapid hip extension, knee extension, and plantarflexion. Collectively, this motion is known as triple extension. The triple extensors function in concert to propel the body during explosive movements. The movement involved with the triple extension can be found in nearly all explosive movements including jumping, sprinting, or tackling. Thus, creating muscle torque rapidly with the triple extensors may be a key for a better performance in most explosive movements.

Since joints are linked together in the human body when the foot is on the ground, motion at one joint causes motion at another joint. For instance, it is known that the gluteus maximus, the primary hip extensor, and the soleus, one of the plantarflexors, are capable of assisting with knee extension in weight-bearing positions, even though they do not cross the knee joint (Levangie & Norkin, 2005). When the foot is on the ground with the knee bent, the contraction of the gluteus maximus creates knee extension and plantarflexion (Levangie & Norkin, 2005). Similar to the gluteus maximus, the soleus can also assist knee extension by pulling the tibia posteriorly when the foot is on the ground (Levangie & Norkin, 2005). Thus, it appears that each muscle group among the triple extensors helps one another generate the efficient triple extension movement.

The contribution of biarticular muscles such as the rectus femoris and gastrocnemius to transfer power from proximal to distal joints has been found in jumping and sprinting (Jacobs, Bobbert & van Ingen Schenau, 1996). Jacobs and colleagues (1996) evaluated the ground reaction force and EMG of eight leg muscles, including the rectus femoris and gastrocnemius, during both a single-leg maximal vertical jump and a maximal sprint push-off among seven elite male athletes. The objective was to determine the amount of power transfer between adjacent joints of the lower extremity due to the biarticular muscles. The results of the study revealed that there was a net transfer of power from the hip joint to the knee joint and finally to the ankle joint during both tasks (Jacobs, Bobbert & van Ingen Schenau, 1996), signifying the importance of the triple extensors working in concert to propel the body.

Based on the previous findings, it appears that each muscle group of the triple extensors contributes to generate the leg extension. Additionally, it also appears that rectus femoris and gastrocnemius function to transfer the power created at proximal joint to distal joint, maximizing efficient torque production during explosive leg extension.

Importance of Rapid Torque Production

Many athletic performances involve explosive types of movement in which an individual is required to rapidly generate muscle torque within a short period of time for better performance. Most traditional measures of muscle torque production have focused primarily on an individual's capability to generate maximal torque (Hicks & McCartney, 1996; Lindeman et al., 1999, and Souza & Powers, 2009). However, the time it takes to reach maximal torque is greater than the time it takes to complete an explosive sporting movement (Luhtanen & Komi, 1979; Dapena & Chung, 1988, and Kuitunen et al., 2002).

While it is known that it takes approximately 250 to 400 ms from the onset of contraction in order to reach peak torque (Aagaard, 2003), Kuitenen and colleagues (2002) reported that the average contact time in young, healthy male sprinters was within approximately 120 ms at 70% running speed and 80 ms at full speed (Kuitunen et al., 2002), indicating that sprinting is executed more quickly than an individual can generate peak torque isometrically. Similar to their findings, Luhtanen and Komi (1979) found that experienced long jumpers had the average take-off contact time of 110 ms while the less experienced long jumpers had the average take-off contact time of 130 ms. This evidence suggests that long jumpers are required to produce torque at the hip, knee and ankle joints in less than time to reach peak torque in order to complete the long jump. Similarly, experienced high jumpers had the average contact take-off time between 180 and 220 ms (Dapena & Chung, 1988), indicating that high jumpers are required to produce torque at the hip, knee and ankle joints in less than time to reach peak torque in order to complete the high jump.

Based on previous findings, it appears that athletic movements such as sprinting, long and high jumping, are executed in less than around 250 ms, which is before an individual can generate the maximal torque isometrically. Therefore, creating the muscle torque rapidly in short period of time is likely more important than the maximal torque production capacity for athletic movements.

Rate of Torque Development

One commonly used measure of rapid torque production is rate of torque development (RTD), sometimes called rate of force development. RTD is defined as the slope of the torque-time curve (Aagaard et al., 2002; Andersen & Aagaard, 2006; Morais De Oliveira et al., 2012, and Zebis et al., 2011). The slope is calculated by fitting a line of best fit onto the torque time curve and measuring the rate of rise of the line.

Previous researchers have examined RTD during different time intervals. One approach has been to measure RTD from onset of contraction to peak torque. Holtermann et al. (2007) measured the RTD from the onset of contraction to peak torque in order to investigate the effect of RTD on peak torque with short-term resistance training. While this approach may be more beneficial than simply measuring peak torque, it may not capture the time intervals that are more closely associated with the functional movements.

More recently researchers have been interested in RTD during time intervals that are associated with shorter, more explosive movements (Aagaard et al., 2002, Anderson & Aagaard, 2006, Anderson et al., 2010, Blazevich et al., 2009, Greco et al., 2013, Hannah et al., 2012, Kyrolainen & Komi, 1994, Maffiuletti et al., 2010, Marshall, McEwen, & Robbins, 2011, Morais de Oliveira et al., 2012, Suetta et al., 2004, Thorlund, Aagaard, & Madsen, 2009, and Waugh et al., 2013). Suetta et al. (2004) mentioned that the researchers chose to evaluate the time period of muscle contraction up to 200 ms based on the fact that many types of movements are characterized by a limited time to develop torque (0-200 ms). In another study, Maffiuletti et al. (2010) evaluated RTD in time periods of 0-50, 0-100, and 0-200 ms from the onset of contraction. The researchers mentioned that these three time periods were examined because of the fact that several daily activities such as descending stairs, walking fast, or preventing a fall after a sudden postural perturbation are characterized by a limited time to generate torque (50 to 200 ms, depending on the activity) and the fact that the steepest RTD was generally obtained within 50 to 100 ms from the onset of contraction with the very large interindividual variability (Maffiuletti et al., 2010). In other studies, Aagaard (2006) and Andersen et al. (2010) evaluated RTD in time period of 0-10, 0-20, 0-30, …, 0-250 ms from the onset of contraction. The researchers insisted it is important to investigate RTD in various time periods from the onset of contraction since different types of explosive movements involve different time spans.

As the previous researchers stated, it appears to be more relevant to measure RTD at time intervals during which explosive movements are executed, instead of measuring RTD from the onset of contraction to peak torque. Moreover, RTD from the onset of contraction to peak torque may not differentiate capability between individual's creating torque during the time intervals during which most explosive movements are executed. For instance, if two individuals exhibited the same peak torque and they both took the same time to reach their peak torque their RTD from the onset of contraction to peak torque would be the same. However, if one individual generated torque more rapidly in the early phase of the torque production while the other individual generated torque more rapidly in the later phase of the torque production, their RTD would be different at time intervals that are associated with explosive movements. Thus, measuring RTD during time intervals that are associated with explosive movements would capture their difference in rapid torque production. Therefore, measuring RTD during time intervals that are associated with explosive movements might be a better approach than measuring RTD from onset of contraction to peak torque.

Measuring Rate of Toque Development of the Triple Extensors

Although previous researchers have investigated RTD of the triple extensors, the muscle groups have typically been tested in isolation. In fact, only one study examined more than one of the triple extensors in the same study (Behm et al., 2002). Furthermore, RTD of the hip extensors have been not been reported in the literature. In this section, common positioning and results of relevant studies will be presented.

RTD of the knee extensors has most commonly been measured from 60° to 90° of knee flexion (0° = full knee extension) (Aagaard et al., 2002; Andersen et al., 2006; Andersen et al., 2010; Behm et al., 2002; Blazevich et al., 2009; Greco et al., 2013; Maffiuletti et al., 2010; Marshall et al., 2011; Morais de Oliveira et al., 2012; Naczk et al., 2010; Suetta et al., 2004; Suetta et al., 2007; Thorlund et al., 2009 and Zebis et al., 2011). Among all, a knee joint angle of 70° has been used as one of the most common knee joint angles to measure RTD of the knee extensors (Aagaard et al., 2002; Andersen et al., 2010; Greco et al., 2013; Marshall et al., 2011; Thorlund et al., 2009 and Zebis et al., 2011). Although this knee joint angle has most frequently been used to measure RTD of the knee extensors, the researchers did not specifically state why they chose to measure RTD of the knee extensors with the knee flexed to 70°. However, it most likely was due to their desire to measure the rapid torque production of the knee extensors at the mid-range of the range of motion – the position where the muscle should be in the optimal position to generate torque.

While many researchers have investigated RTD of the knee extensors, researchers have less frequently investigated RTD of the plantarflexors. Isometric contraction of the plantarflexors has previously been measured at various knee and ankle joint angles (Behm et al., 2002; Del Balso & Cafarelli, 2007; Holtermann et al., 2007; Power et al., 2004 and Waugh et al., 2013). A neutral position of the ankle joint angle has been used as one of the most common joint angles to measure the isometric contraction of the plantarflexors (Behm et al., 2002; Del Balso & Cafarelli, 2007 and Waugh et al., 2013).

Although the authors chose the joint angle to measure the isometric contraction of the plantarflexors, they did not specifically state why they chose this joint angle. Meanwhile, other researchers measured the isometric contraction of the plantarflexors at slightly dorsiflexed position (10° from a neutral position) (Power et al., 2004 and Holtermann et al., 2007). Although Holtermann et al. (2007) did not state a specific rationale of choosing this joint angle, Power et al. (2004) stated that this joint angle is optimal for plantarflexors to generate torque.

Besides the ankle joint angle, the knee joint angle would affect torque production of the plantarflexors due to the fact that a change in knee angle changes the involvement of the gastrocnemius. Given that the proximal attachments of the gastrocnemius originate from the condyles of the femur, the gastrocnemius can produce greater plantarflexion torque with the knee in full extension (Cresswell, Löscher, & Thorstensson, 1995). As knee flexion angle increases, the plantarflexion torque production capacity of the gastrocnemius decreases (Cresswell, Löscher, & Thorstensson, 1995).

Waugh et al. (2013) tested the isometric contraction of the plantarflexors with full knee extension. While the authors did not mention a rationale of testing with knee fully extended, it most likely was due to measuring the peak torque of the plantarflexors combined with the soleus and gastrocnemius. Contrary to Waugh et al. (2013), Del Balso & Cafarelli (2007) and Power et al. (2004) tested the isometric contraction of the plantarflexors with 90° of knee flexion. Power and colleagues (2004) tested in that position because the researchers were interested in the effect of moderate amount of static stretching on torque production of the soleus. Similarly, Holtermann et al. (2007) tested the isometric contraction of the plantarflexors at ~80° of knee flexion. Del Balso &

Cafarelli (2007) and Holtermann et al. (2007) tested in that position because both groups were interested in the effects of alterations of the neural function following the resistance training on torque production of the soleus.

While RTD of the hip extensors has not been tested previously, peak torque of the hip extensors has been tested. Isometric contraction of the hip extensors has been measured at 30°, 45°, and 90° of the hip flexion previously (Cahalan et al., 1989 and Souza & Powers, 2009). Souza and Powers (2009) positioned the participants in prone with their tested leg at 30° of hip flexion and 90° of knee flexion. The subjects were instructed to push as hard as possible for five seconds. While the authors did not specifically state why they chose to position the participants in prone with the hip flexed to 30° and the knee flexed to 90°, it most likely is due to measuring torque production of the gluteus maximus in the optimal position to generate torque with little involvement of the hamstrings.

Contrary to Souza and Powers (2009), Cahalan et al. (1989) tested the isometric contraction of the hip extensors in standing position. The authors used the Cybex II isokinetic dynamometer with a body stabilization frame to measure the isometric contraction of the hip extensors. The isometric contraction of the hip extensors was tested at 45° and 90° of hip flexion with the knee flexed to 90°. Although the authors did not provide rationale for their choice of positioning, it was most likely due to the desire to test the hip extensors at two different positions around the mid-range.

As mentioned, only one study investigated RTD of more than one of the triple extensor muscle groups in the same population (Behm et al., 2002). In that study, the researchers investigated differences in the RTD of the knee extensors and the plantarflexors (as well as the dorsiflexors and elbow flexors) in 12 physically active, male university students by measuring rapid isometric contraction of each muscle group. They measured RTD from onset of torque production to peak torque. They reported both non-normalized RTD and normalized to peak torque RTD. The researchers reported non-normalized RTD of the knee extensors was 58.3% greater than that of the plantarflexors. While normalized RTD of the knee extensors was 32.1% greater than that of the plantarflexors.

Based on previous studies, measurement of RTD and peak torque of the knee extensors and plantarflexors has been mostly measured while seated and with the joint of interest near the mid-range of motion. Additionally, many researchers have measured peak torque of the plantarflexors in the seated position with the knee flexed to 90°; this testing position would reduce the involvement of the gastrocnemius, the primary plantarflexor, in torque production. Therefore, in order to measure RTD of both the soleus and gastrocnemius the knee should be as fully extended as possible. Lastly, peak torque of the hip extensors although rarely reported has been measured either in the seated or in the standing position with hip joint in varying positions of hip flexion.

CHAPTER 3 – MATERIALS AND METHODS

Participants

Thirty recreationally active participants (15 females and 15 males, age: 23 ± 2.5 years, body height: 172.8 ± 9.5 cm, body mass: 72.2 ± 14.0 kg) volunteered to participate in the study approved by the University's Institutional Review Board. For this study, recreationally active was defined as engaging in moderate intensity exercises for at least 150 minutes per week (Garber et al., 2011). Exclusion criteria included: 1) current injuries or illnesses that limited their ability to perform physical activity, 2) lower extremity or back injuries in the six months prior to testing that limited their regular physical activity, or 3) history of hip, knee, or ankle surgery. All participants were asked to not perform any strenuous, fatiguing physical activity prior to testing on the day of testing.

Procedures

Participants reported to the Biomechanics Laboratory for consent, eligibility screening, and testing. Following consent and screening, participants were asked to warm-up on a stationary bicycle for five minutes at a submaximal intensity. Following warm up on the bike, leg dominance was determined by which leg the participant used for the majority of the following three tasks: 1) kicking a ball, 2) stepping up onto a 20-centimeter-high step box, and 3) recovering from a small perturbation from behind (Hoffman et al., 1998). The participants were then asked to remove his or her shoes and height in centimeters (cm) was measured using a wall mounted stadiometer and body mass in kilograms (kg) was determined using a standard scale.

Rate of Torque Development

RTD of the hip extensors, knee extensors, and plantarflexors of the dominant leg were measured during a maximal isometric contraction using a Biodex System 3 dynamometer (Biodex Medical Systems Inc., Shirley, New York, USA) interfaced with a BIOPAC MP100 Data Collection System (BIOPAC systems Inc., Goleta, California, USA). The participants were instructed to contract "as hard and fast as possible" for three to five seconds against the dynamometer following presentation of a light stimulus. Immediately following each trial, trials were visually inspected for the presence of an initial countermovement and to ensure the torque-time curve reached a plateau (signifying maximal torque). Any trials with either condition were disregarded and repeated. Three valid trials out of a maximum of five trials were collected. Between each trial, 60 seconds of rest was provided. In order to eliminate any potential effects of learning or fatigue on the RTD measures, the order of testing for the muscle groups was counterbalanced. Data were sampled at 1000 Hz.

RTD of the Hip Extensors

To measure RTD of the hip extensors, participants were positioned prone with both lower extremities off the edge of the dynamometer table (Souza & Powers, 2009) (see Figure 1). The greater trochanter of the test leg was aligned with the axis of rotation of the dynamometer. The dynamometer resistance pad was positioned on the distal aspect of the hamstrings just above the popliteal fossa. A standard goniometer was used to position the hip and knee in 30° and 90° of flexion respectively. The non-test leg supported the body. To prevent trunk extension, the participant's arms were wrapped around the dynamometer chair and the trunk stabilized with a resistance strap over the lower back. The participants were instructed to push as hard and fast as possible against the dynamometer without extending the trunk or flexing the knee following presentation of a light stimulus.

RTD of the Knee Extensors

RTD of the knee extensors was assessed with the participants seated on the chair of the dynamometer with the trunk flexed to 70° and the knee flexed to 70º (0º = full knee extension) (Aagaard et al., 2002; Andersen et al., 2010; Greco et al., 2013; Marshall et al., 2011; Thorlund et al., 2009 and Zebis et al., 2011). Positioning was confirmed using a standard goniometer. The axis of rotation of the dynamometer was visually aligned to the lateral femoral epicondyle of the test leg. The resistance pad was firmly strapped over the musculotendinous junction of the gastrocnemius. To prevent hip motion, the thigh of the test leg and the pelvis were firmly strapped to the dynamometer. The arms were crossed over the chest during the testing. The participants were instructed to extend the knee as hard and fast as possible against the dynamometer arm following presentation of a light stimulus.

RTD of the Plantarflexors

In order to evaluate RTD of the plantarflexors, participants were seated on the chair of the dynamometer with the trunk flexed to 70°. The foot on the test leg was placed on the dynamometer foot plate with the knee flexed to 15°. This knee angle was determined by pilot studies to measure RTD of the plantarflexors. The axis of the rotation of the dynamometer was visually aligned with the lateral malleolus of the test leg. The foot was firmly strapped to the foot plate with the ankle joint in neutral position (i.e., anatomical position). The positions were confirmed using a standard goniometer. The arms were crossed over the chest during the measurement. The participants were also instructed to push as hard and fast as possible against the foot plate by plantarflexing their ankle as if pushing on a gas pedal following presentation of a light stimulus.

Data Analysis

Following data collection the data were analyzed using a custom built LabView (National Instruments, Austin, Texas) program. The torque signal was low-pass filtered using a digital fourth-order, zero-lag Butterworth filter, with a cutoff frequency of 10 Hz. To account for the weight of the limb and the dynamometer attachment, the average of the first 500 samples during the quiet period prior to torque onset was calculated and subtracted from the torque signal. RTD was calculated as the slope of the line of best fit of the torque-time curve over time intervals of 0 – 25, 0 – 50, 0 – 100, 0 – 150, 0 – 200, and 0 – 250 milliseconds (ms) relative to onset of muscle contraction. Onset of muscle contraction was defined as the point at which the torque exceeded 2.5 % of the measured peak torque (Aagaard et al., 2002). Four trials (two hip extensions and two plantarflexions) were not used for further analysis because offsets were not established. RTD data were normalized to body mass$^{0.67}$(kg) (Jaric, Mirkov, & Markovic, 2005).

Statistical Analysis

The Pearson product moment correlation coefficients were used to determine the relationship of RTD between the triple extensors (hip extensors, knee extensors, and plantarflexors) during each of the six time intervals: 0-25, 0-50, 0-100, 0-150, 0-200, and 0-250 ms. An alpha level was set a prior = 0.05. All statistical procedures were performed in IBM SPSS Statistics 19.0 (IBM, Armonk, New York, USA).

Figure 1. Hip extension RTD testing position using the Biodex dynamometer.

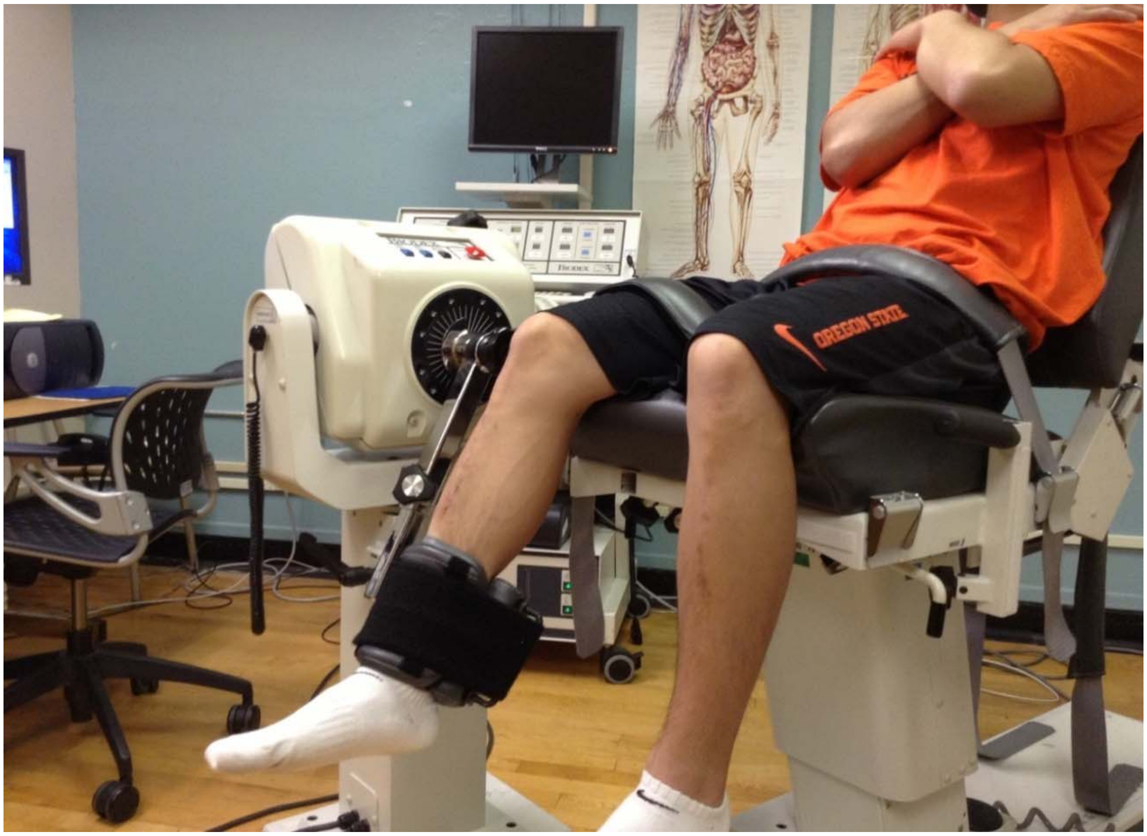

Figure 2. Knee extension RTD testing position using the Biodex dynamometer.

Figure 3. Plantarflexion RTD testing position using the Biodex dynamometer.

CHAPTER 4 - RESULTS

Means and standard deviations for each variable are presented in Table 1, while correlation coefficients of RTD between: hip extensors (HE) and knee extensors (KE), KE and plantarflexors (PF), and HE and PF are presented in Table 2. Greater RTD of the HE was associated with greater RTD of the KE at: 0-25 ms $r=0.676$ ($p \leq 0.01$), 0-50 ms $r=0.719$ ($p \leq 0.01$), 0-100 ms $r=0.661$ ($p \leq 0.01$), 0-150 ms $r=0.679$ ($p \leq 0.01$), 0-200 ms $r=0.582$ ($p \leq 0.01$), and 0-250 ms $r=0.452$ ($p \leq 0.05$). Greater RTD of the KE was associated with greater RTD of the PF at: 0-25 ms $r=0.730$ ($p \leq 0.01$), 0-50 ms $r=0.758$ ($p \leq 0.01$), 0-100 ms $r=0.777$ ($p \leq 0.01$), 0-150 ms $r=0.802$ ($p \leq 0.01$), 0-200 ms $r=0.814$ ($p \leq 0.01$), and 0-250 ms $r=0.803$ ($p \leq 0.01$). Greater RTD of the HE was associated with greater RTD of the PF at: 0-25 ms $r=0.663$ ($p \leq 0.01$), 0-50 ms $r=0.767$ ($p \leq 0.01$), 0-100 ms $r=0.818$ ($p \leq 0.01$), 0-150 ms $r=0.783$ ($p \leq 0.01$), 0-200 ms $r=0.650$ ($p \leq 0.01$), and 0-250 ms $r=0.563$ ($p \leq 0.01$).

Table 1. Means and standard deviations (SD) RTD of the triple extensors at 0-25, 0-50, 0-100, 0-150, 0-200 and 0-250 ms. Mean ± SD ($Nm \cdot s^{-1} \cdot [kg^{0.67}]^{-1}$)

	0-25 (ms)	**0-50**	**0-100**	**0-150**	**0-200**	**0-250**
HE	15.36 ± 6.94	20.76 ± 11.00	34.94 ± 24.34	42.22 ± 26.12	36.96 ± 17.79	29.32 ± 11.99
KE	24.67 ± 14.57	38.10 ± 24.14	48.66 ± 28.31	39.07 ± 18.60	31.09 ± 13.42	26.78 ± 10.67
PF	14.55 ± 5.96	19.47 ± 8.94	24.67 ± 11.98	23.40 ± 11.06	20.11 ± 9.06	17.59 ± 7.63

Table 2. Correlation coefficients (r) of RTD between the hip extensors (HE) and knee extensors (KE), KE and plantarflexors (PF), and HE and PF.

	0-25 (ms)	**0-50**	**0-100**	**0-150**	**0-200**	**0-250**
HE vs. KE	0.676**	0.719**	0.661**	0.679**	0.582**	0.452*
KE vs. PF	0.730**	0.758**	0.777**	0.802**	0.814**	0.803**
HE vs. PF	0.663**	0.767**	0.818**	0.783**	0.650**	0.563**

* $p \leq 0.05$, ** $p \leq 0.01$

CHAPTER 5 - DISCUSSION

The purpose of the study was to investigate the relationship of RTD between the triple extensors at different time intervals after the onset of contraction, specifically 0-25, 0-50, 0-100, 0-150, 0-200, and 0-250 ms. During the first 50 ms (i.e., 0-25 and 0-50 ms) the correlations were very similar among all three muscle groups. However, after that time period the relationships between the muscle groups diverged. Specifically relationships of RTD of the HE and KE was highest at the 0-50 ms time interval and then decreased at the later time intervals. While relationships of RTD of the KE and PF remained quite consistent with correlation coefficients that only varied by 0.084 over the different time intervals, relationships of RTD of the HE and PF increased up to the 0-100 ms time interval and then lowered at the later time intervals (see Figure 4).

The fact that the correlation between the KE and PF remained high across all the time intervals might be explained by the fact that both muscle groups had similar patterns of RTD. As can be seen in Figure 5, both muscle groups' RTD was the greatest at 100 ms from the onset of contraction. Moreover, RTD of the KE at early phases of the torque production (≤100 ms after the onset) was greater than at late phases of the torque production (≥150 ms after the onset). Similar to RTD of the KE, RTD of the PF at early phases of the torque production was greater than at late phases of the torque production (see Figure 5). Furthermore, the shared variance between RTD of the KE and PF stayed high (64.5% - 53.3%) throughout all the time intervals.

Contrary to RTD of the KE and PF, RTD of the HE exhibited a different pattern of rapid torque production. As can be seen in Figure 5, the HE's RTD was the greatest at 150 ms from the onset of contraction, suggesting that the HE took more time to reach maximal rate of torque production than the other two muscle groups. This notion might explain our findings of the lower relationship of RTD between the HE and the other two muscle groups towards the later phase of the torque production (≥150 ms after the onset) (see Figure 4). Furthermore, unlike the shared variance between the KE and PF, the shared variance between the HE and the other two muscle groups was reduced at the later phase of the torque production. The shared variance between the HE and KE decreased from 51.7% in the first 50 ms to 20.4% at 250 ms from the onset of contraction. Likewise, the shared variance between the HE and PF decreased from 66.9% in the first 100 ms to 31.7% at 250 ms from the onset of contraction. These observed decreases in the shared variances could suggest that the HE and the other two triple extensor muscle groups differ in their patterns of rapid torque generation.

The current results are in agreement with previous research on RTD of the KE and PF. Behm et al. (2002) compared the KE and PF RTD normalized to maximal voluntary contraction in 12 physically active, male university students. They reported that RTD of the knee extensors was greater than that of the plantarflexors, which corresponds to the finding that RTD of the knee extensors was greater than the plantarflexors. However, no other researchers have examined RTD of the HE.

Although the current results cannot fully explain why the HE pattern of rapid torque production appeared to be different than the other two triple extensor muscle groups, there are several possible reasons that might explain this, including neural and muscular factors of each muscle group such as skeletal muscle fiber type distribution, motor neuron size, and muscle architecture.

Similarities and differences in the skeletal muscle fiber type distribution among the triple extensors might partially explain the findings. Skeletal muscle fibers are generally categorized into two different types: type I and II. While several factors differentiate the fiber types, one of the main factors is shortening velocity. Type I fibers are also known as slow twitch fibers because contraction speed of type I fibers is slower than that of type II fibers (Lieber, 2002, Chapter 2); on the other hand, type II fibers are also known as fast twitch fibers because contraction speed of the type II fibers is faster than that of type I fibers (Lieber, 2002, Chapter 2). Therefore, muscles comprised of more type II fibers generate torque more rapidly (Aagaard and Andersen, 1998; Harridge et al., 1995; Harridge et al., 1996 & Metzger and Moss, 1990). Moreover, type II fibers can be further broken down into three different types – IIA, IIX, and IIB. It is known that contraction speed of the type IIB is the fastest among the type II fibers, while that of the type IIX is the second fastest and type IIA has the slowest contraction speed among the type II fibers (Lieber, 2002, Chapter 2).

Although specific fiber types of the muscles were not collected in this study, previous researchers have reported that the fiber type distribution in the muscles of triple extension is different. Johnson et al. (1973) reported the following mean percentage of type II fibers in the quadriceps: 70.5% in the rectus femoris, 67.3% in the vastus lateralis, 56.3% in the vastus medialis. They also found the percentage of type II fibers in lateral and medial gastrocnemius was 56.5% and 49.2%, respectively, whereas the mean percentage of type II fibers in soleus was 13.6% (Johnson et al., 1973). Additionally, the gluteus maximus was comprised of 47.6% of type II fibers. Although the researchers did not investigate the distribution of different types of type II fibers, according to their findings, it appears that the gluteus maximus, a primary hip extensor, had the lowest mean percentage of type II fibers among the triple extensors, except the soleus. In the present study, the greatest RTD of the HE was later than the other two triple extensors. Thus, the mean percentage of type II fibers appears to correspond with rapid torque production.

A more recent study examined the changes in muscle fiber type and RTD following a high-intensity resistance training program in 15 healthy, sedentary young males (Andersen et al., 2010). The researchers reported an increase in RTD of the knee extensors following the intervention. They also reported a decrease in type IIX fibers and the increase in type IIA fibers through the resistance training program. According to their multiple regression analysis, decrease in type IIX fibers could explain 38% of the decrease in early RTD normalized to MVC. Based on their findings, they concluded that decreased type IIX fibers by the resistance training appeared to partially contribute to decrease normalized RTD in early phase of the torque production. The researchers claimed that such a fiber type transition occurred possibly because the participants were instructed to train in a controlled manner as opposed to training in an explosive manner. In the present study, the greatest RTD of the HE was later than the other two triple extensors. However, since the breakdown of the type II fibers is not known of the muscles of the triple extensors, further investigation is warranted.

Furthermore, it is known that the different types of muscle fibers are closely associated with different sizes of motor neurons. A motor unit consists of one alpha motor neuron and all the muscle fibers it innervates. The size of the motor unit corresponds to the diameter of the axons (Lieber, 2002, Chapter 2). The larger the diameter of the axons, the shorter the time the nerve impulses take to travel through the axons to reach the muscle fibers (Lieber, 2002, Chapter 2). Larger diameter motor neurons innervate primarily type II fibers and are known as large motor units, whereas smaller diameter axons innervate more type I fibers and are known as small motor units (Burke, 1967, and Burke et al., 1971). Therefore, muscles that are primarily comprised of slow twitch fibers have a larger percentage of small diameter motor neurons and the reverse is true for primarily fast twitch muscles. As mentioned previously, the gluteus maximus is comprised of the lower mean percentage of type II fibers than the quadriceps and gastrocnemius, indicating that the size of the motor units in the gluteus maximus may be smaller than the quadriceps and gastrocnemius.

The size of the motor unit is important in terms of the order of recruitment of the motor units. Based on the size principle of motor unit recruitment, in order to produce torque, smaller motor units are recruited first followed by progressively larger motor units as increased torque production is needed (Lieber, 2002, Chapter 2). As previously mentioned, the primary difference between slow twitch and fast twitch fibers is the contraction speed. Therefore, in order to produce force as rapidly as possible, it would be beneficial to recruit the larger motor units as quickly as possible. However, the smaller motor units will always be recruited first which provides a natural limitation to how fast torque production will occur due to motor unit recruitment.

In addition to increasing torque production through motor unit recruitment, the motor units can be activated more frequently. This is known as increased rate coding and occurs when a motor unit sends action potentials to the muscle resulting in the muscle fibers being activated more frequently, ultimately leading to greater torque production.

Furthermore, if two motor units are activated at the same time, i.e., they synchronize their firing, then the muscle will also generate more torque. In fact both of these mechanisms, increased rate coding and increased motor unit synchronization have been suggested to be important for increasing RTD (Aagaard et al., 2002, and Semmler, 2002).

While the actual motor unit recruitment pattern and rate coding of the triple extensors is not known, based on the muscle fiber type distribution it would be logical that the gluteus maximus would have a motor neuron pool that is comprised of fewer larger motor units compared to the quadriceps and gastrocnemius motor neuron pools. This could impact both motor unit recruitment and rate coding.

Similarities and differences in muscle fiber architecture among the triple extensors might also explain our findings. Muscle fibers are classified into two common types of arrangements: fusiform and pennate (Premkumar, 2004, Chapter 4). In fusiform muscles, the fibers run parallel along the length of the muscle such as in the biceps brachii (Premkumar, 2004, Chapter 4). All of the triple extensors are pennate muscles, muscles with fascicles that attach obliquely to their tendons (Premkumar, 2004, Chapter 4). Pennate muscles are further classified into unipennate, bipennate, and multipennate. Unipennate muscles have all the fascicles on the same side of the tendon, such as the extensor digitorum longus. Bipennate muscles have fascicles on both sides of the central tendon, such as the rectus femoris. A muscle is called multipennate when the central tendon branches within a pennate muscle such as the gluteus maximus (Premkumar, 2004, Chapter 4).

One mechanical advantage of pennate muscles is that more sarcomeres can be arranged in parallel than in fusiform muscles. With more sarcomeres in parallel, the muscle has a larger physiological cross-sectional area (PCSA). PCSA is defined by dividing the muscle volume by its fiber length and is proportional to the maximum strength of the muscle. Although the pennate muscles are arranged to generate more force, their contraction speed is slower than the fusiform muscles in which the sarcomeres are more in series. Judging from the sarcomere arrangement and PCSA, the multipennate muscle like the gluteus maximus appears to be arranged to produce greater force than the bipennate muscle like the rectus femoris and gastrocnemius, while being arranged to take more time to generate force than the bipennate muscles.

In addition to the differences in pennation angle between the triple extensors, the lines of pull thus the functions of the muscles are different. The gluteus maximus is known as the primary hip extensor, but also rotates the femur externally (Levangie & Norkin, 2005). In addition to its function as a torque producer, the gluteus maximus is also considered as an important stabilizer of the lumbo-pelvic region, specifically at the sacroiliac joint. These functions of the gluteus maximus were confirmed by Gibbons and Mottram (2004) dissecting the gluteus maximus of twelve cadavers. The researchers identified the three components in the gluteus maximus: superficial sacral fibers, deep sacral fibers, and deep ilium fibers. They also identified that each fiber attached into the different locations, suggesting that each fiber has a different function. Thus, it appears that the gluteus maximus not only generates torque in multiple planes (sagittal, transverse and frontal), but it also functions as both a hip joint and trunk stabilizer. These features of the gluteus maximus separate the muscle from the other two primary triple extensors, the rectus femoris and gastrocnemius. Although both rectus femoris and gastrocnemius are primary torque producers of knee extension and plantarflexion, respectively, these motions occur primarily only in a single plane – the sagittal plane. Because of the difference in the line of pull of the muscles between the gluteus maximus and the other two primary triple extensors, it appears that while both the rectus femoris and gastrocnemius are structured primarily for rapid torque production, the gluteus maximus appears to be structured to generate torque simultaneously with stabilizing both the hip joint and the posture. Consequently, the gluteus maximus might take more time to generate torque rapidly than the other muscle groups, which was observed in the present study. Taken together, because of the possible differences in fiber type distribution, motor unit size, pennation angles, and the line of pull, the gluteus maximus is different than the other two triple extensors.

A general limitation of the study was that while triple extension is a dynamic movement involving the three joints of the lower extremity working together to propel the body, all of the testing in this study were done statically. For instance, to test HE, participants were positioned in prone with the knee flexed at 90° because the goal was to measure the RTD of the gluteus maximus, the primary hip extensor. To test the KE, participants were in a seated position with the knee flexed to 70° whereas to test the PF, participants were in a seated position with the knee flexed to 15° and the ankle joint in neutral position. While all of the positions were static, they were performed in mid-range which is the position that should produce their greatest amount of torque in static position.

Another limitation of the study was that neither EMG nor muscle biopsy was used to measure fiber type composition in the study. Thus, it remains unknown which neural and muscular properties of the triple extensors in recreationally active, young populations contribute to the findings.

Due to these limitations, it remains to be determined what contributes to the relationship of RTD between the triple extensors in terms of neural and muscular aspects. Nonetheless, the results of the present study provide a starting point for future study. A next relevant step may be to study potential neural and muscular contributors to RTD of the triple extensors by using EMG and muscle biopsy.

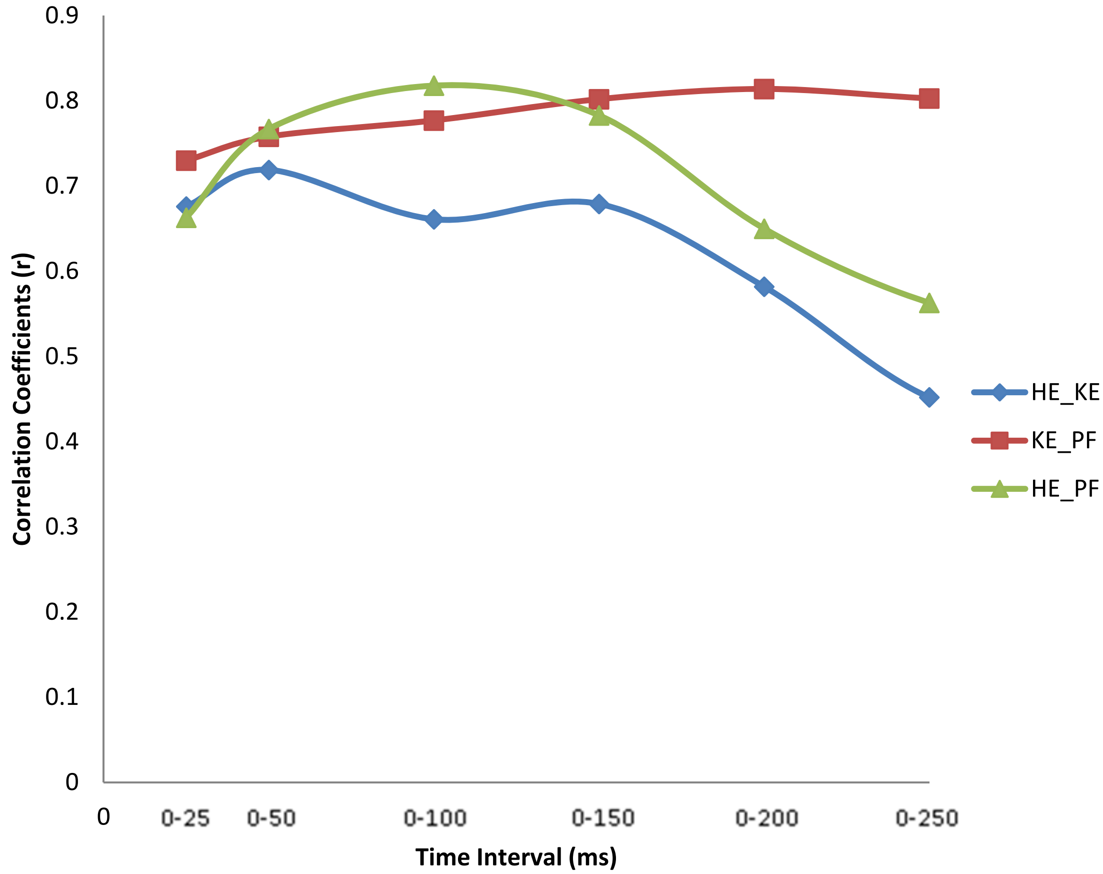

Figure 4. Correlation Coefficients between RTD of the HE and KE, the KE and PF, and the HE and PF at 0-25, 0-50, 0-100, 0-150, 0-200, and 0-250 ms.

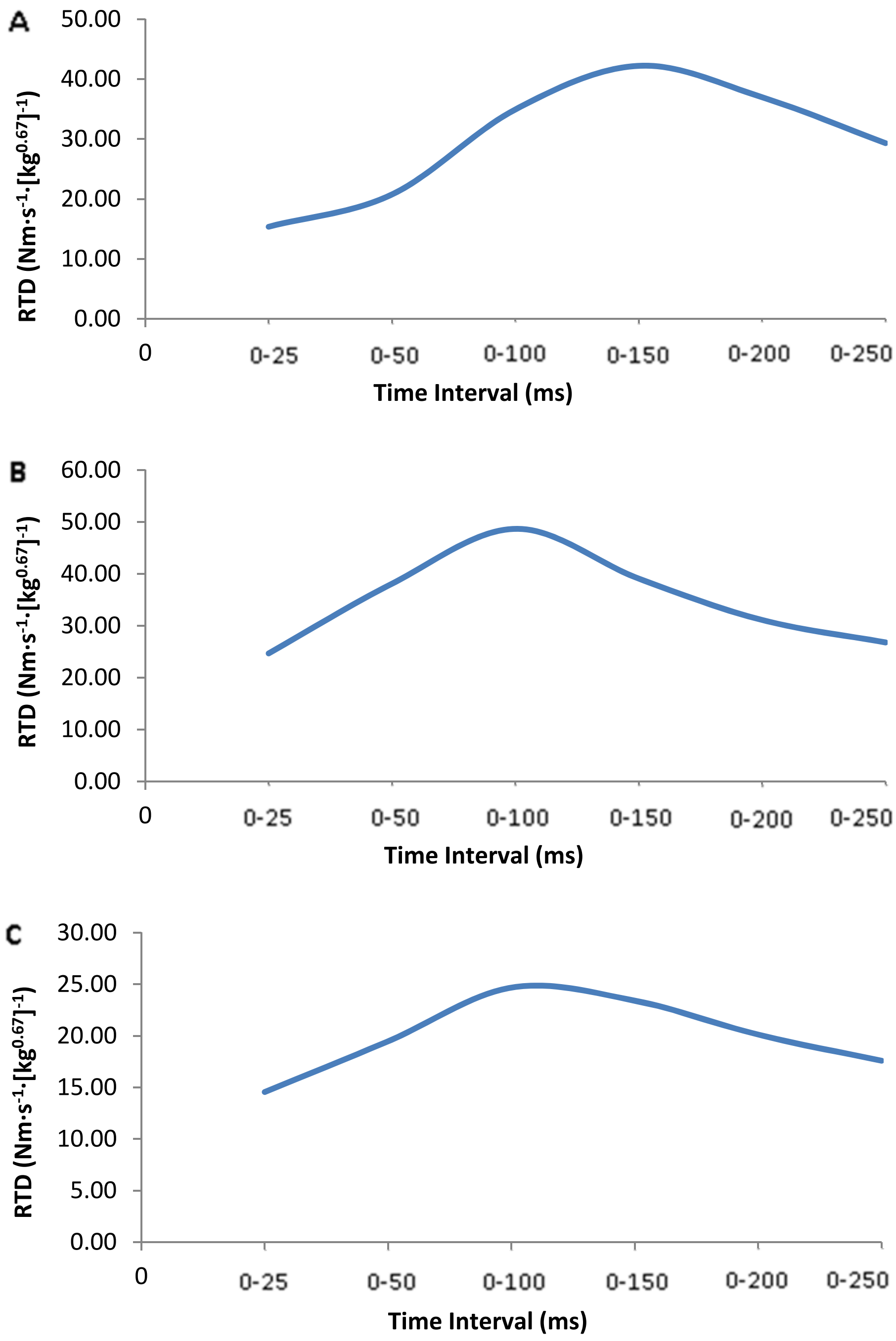

Figure 5. RTD at 0-25, 0-50, 0-100, 0-150, 0-200 and 0-250 ms. A) Hip extensors, B) Knee extensors, and C) Plantarflexors.

CHAPTER 6 – CONCLUSION

The triple extensors in the lower extremity work together in order to propel the body during explosive movements. Therefore, the capacity of these three muscle groups to rapidly generate torque is likely important for optimal performance. However, the relationship between RTD of the triple extensors during the critical time periods that are associated with explosive movements up to this point were unknown.

The results demonstrated that while the relationship between the RTD of the knee extensors and plantarflexors remained high across all the time intervals, the relationship between the RTD of the hip extensors and the other two triple extensors declined after 150 ms from the onset of contraction in young, healthy, recreationally active populations. The relationship between the RTD of the knee extensors and plantarflexors might suggest that these muscles exhibited the similar patterns of rapid torque production; in contrast to the hip extensors.

While the neural and muscular properties of the triple extensors remain uncertain, such an observed difference between the RTD pattern of the hip extensors and the other two triple extensors might be explained by the difference in fiber type distribution, sizes and types of motor units, and muscle fiber architecture.

Although this is the first study to report the relationship between the RTD of the triple extensors at different time intervals, exact contributors to the observed relationships remain uncertain. Thus, future study should attempt to investigate both the neural and muscular aspects of the triple extensors during rapid torque production. In addition, practitioners should consider how to improve rapid torque production of the hip extensors for better performance in explosive movements.

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APPENDICIES

APPENDIX A: INFORMED CONSENT

CONSENT FORM

Project Title:	The Relationship of Rapid Torque Production of the Triple Extensors and Maximum Vertical Jump
Principal Investigator:	Sam Johnson, PhD, ATC
Student Researcher:	Taichi Kitagawa, ATC; Eunwook Chang, MS, ATC; Roy Almog; Dylan Wile
Co-Investigator(s):	Marc Norcross, PhD, ATC; Eunwook Chang, MS, ATC
Sponsor:	No Sponsor
Version Date:	02/25/2013

1. WHAT IS THE PURPOSE OF THIS FORM?

This form contains information you will need to help you decide whether to be in this study or not. Please read the form carefully and ask the study team member(s) questions about anything that is not clear.

2. WHY IS THIS STUDY BEING DONE?

The ability to rapidly produce strength is important in athletic movements and in injury prevention. However it is unknown if a person who is able to produce strength rapidly in one muscle can also produce strength rapidly in other muscles or during a jumping movement. Therefore, the purpose of this study is to investigate the relationship between how quickly the muscles that extend your hip, extend your knee, and plantarflex your ankle can produce strength. Additionally, we will investigate the relationship between strength of those muscles and a maximal vertical jump. Up to 40 participants may be enrolled to take part in this study. This research will be used as part of a student master's thesis.

3. WHY AM I BEING INVITED TO TAKE PART IN THIS STUDY?

You are being invited to take part in this study because you meet ALL of the following requirements:

1) You are between the ages of 18 – 30,
2) You are recreationally active at least 150 minutes per week,
3) You have no current injuries or illness that limit your ability to perform your regular physical activity,
4) You have had no leg or low back injuries in the last 6 months that limited your regular physical activity, and
5) You have no history of hip, knee or ankle surgery.

Additionally you are being asked to not perform any strenuous, fatiguing physical activity prior to testing on the day of data collection. This is being done in order to prevent fatigue from affecting the test results. If you do perform any strenuous, fatiguing physical activity prior to testing on the day of data collection we will ask you to reschedule testing to another day.

4. WHAT WILL HAPPEN IF I TAKE PART IN THIS RESEARCH STUDY?

The study will take place during one visit, approximately 60 minutes in length, in the Women's Building. The following is a brief description of the testing session:

1) Consent and eligibility screening (~15 mins)
    - You will provide written consent to participate in this study by reading and signing this informed consent document.
    - You will complete a screening questionnaire to ensure you meet the conditions to be in the study.
2) Warm-up (~5 mins)
    - You will be asked to warm up on a stationary bicycle for five minutes at a submaximal intensity.
3) Determination of leg dominance, height, and weight (~5 mins)
    - Your leg dominance will be determined by the following three criteria: 1) leg used to kick a ball, 2) leg used to step up onto a step, and 3) the leg used to recover from a small push from behind.
    - Your height and weight will be measured with your shoes off.
4) Strength testing (~25 mins)
    - You will be positioned on a dynamometer which is a device that measures muscle strength. Once you are positioned your ability to produce rapid, maximal muscle strength of the following muscle groups: hip extensors (gluteus muscles of your hip), knee extensors (quadriceps muscles of your thigh), and ankle plantarflexors (triceps surae muscles of your calf) will be measured.
        - For the hip extensors (muscles that push your thigh backwards) you will be on your stomach with your legs off the dynamometer bench. The dynamometer attachment will be secured just above your knee. You will be asked to push against the attachment by pushing your thigh backwards against the pad.
        - For the knee extensors (muscles that push your shin out) you will be seated with your knee bent and the attachment just above your ankle. You will be asked to extend your knee / push your shin out against the pad.
        - For the ankle plantarflexors (muscles that point your toes down) you will be seated with your knee slightly bent and your foot secured to the attachment. You will be asked to push against the attachment like you would push on the gas pedal of a car.
    - For each muscle group you will be instructed to push against the dynamometer attachment as fast and as hard as you can once you see a light. The attachment will not move but your strength will still be recorded. Each trial will last no longer than 5 seconds with 60 seconds rest between trials. A maximum of 5 trials will be collected for each muscle group. The order of testing will not be the same for everyone.
5) Vertical jump testing (~10 mins)
    - You will put your shoes on and your maximum vertical jump height will be measured using a Vertec jump height measurement device and a force plate. You will stand with your feet shoulder width apart on a forceplate and jump and touch as high as possible on the plastic measurement markers of the Vertec. The forceplate is a piece of equipment embedded in the ground that measures the forces you exert on the ground. You will perform up to 5 vertical jumps with 60 seconds rest between each jump.

Storage and Future use of data:
It is not possible for us to know what studies we may do in the future. We ask that you give permission now for us to use your personal information without being contacted about each future study. Future use of your information will be limited to studies about exercise, strength, neuromuscular performance, and injury. If you decide later that you do not want your information stored for future use, you may contact Sam Johnson (sam.johnson@oregonstate.edu).

______You may store my information for use in future studies.
Initials

______ You may not store my information for use in future studies.

Initials

Future contact: We may contact you in the future for another similar study. You may ask us to stop contacting you at any time.

Study Results: If you request to see your strength and/or vertical jump measurements we will be able to provide them at the conclusion of the study. Please contact us for that information.

5. WHAT ARE THE RISKS AND POSSIBLE DISCOMFORTS OF THIS STUDY?

Muscle strength testing is commonly done in the clinical setting. We believe the risks involved in the study are minimal and that we have taken the necessarily steps to protect you. To the best of our knowledge, we have identified any potential risks and/or discomforts that you may experience as a result of being in this study. However, you may experience side effects from the study procedures that are not known to us. This information will help you decide whether to be in this study or not.

Measurement of muscle strength and vertical jump may cause mild temporary discomfort, such as fatigue, muscle strains, or muscle soreness, during the testing and a few days following the testing. In order to limit this you will warm-up on a stationary bike prior to any strength and jump testing. Additionally, rest periods will be provided between strength and jump testing trials. If you feel uncomfortable and wish to stop testing for any reason, you may tell the researcher and end the test or the test session at any time.

We have procedures in place to protect your privacy. However, there is a small risk that we could accidentally disclose information that identifies you. Please see the section "WHO WILL SEE THE INFORMATION I GIVE?" for our procedures to minimize your risk.

6. WHAT HAPPENS IF I AM INJURED?

Oregon State University has no program to pay for research-related injuries. You will be responsible for all costs associated with receiving medical treatment. Compensation will not be provided. If you think that you have been injured from being in this study, please report what happened to the student researcher and/or the principal investigator immediately. The information will be reported immediately to the Oregon State University Institutional Review Board (a committee that reviews and approves research studies).

7. WHAT ARE THE BENEFITS OF THIS STUDY?

This study is not designed to benefit you directly.

8. WILL I BE PAID FOR BEING IN THIS STUDY?

You will not be paid for being in this research study.

9. WHO WILL SEE THE INFORMATION I GIVE?

The information you provide during this research study will be kept confidential to the extent permitted by law. Research records will be stored securely and only researchers will have access to the records. Federal regulatory agencies and the Oregon State University Institutional Review Board (a committee that reviews and approves research studies) may inspect and copy records pertaining to this research. Some of these records could contain information that personally identifies you.

To help protect your privacy, all information that we collect about you will not be directly associated with your name. Instead, we will use a unique identification code on data forms instead of your name. Your information will be stored either on a laboratory or researchers' password protected computer, on a computer or in a locked file cabinet that is in the researchers' laboratory or office.

If the results of this project are published, your identity will not be made public.

10. WHAT OTHER CHOICES DO I HAVE IF I DO NOT TAKE PART IN THIS STUDY?

Participation in this study is voluntary. If you decide to participate, you are free to withdraw at any time without penalty. You will not be treated differently if you decide to stop taking part in the study. If you choose to withdraw from this project before it ends, the researchers may keep information collected about you and this information may be included in study reports.

Participation terminated by investigator: Subject's participation may be terminated by the investigator without regard to the subject's consent, if subject does not follow instructions for study activities.

11. WHO DO I CONTACT IF I HAVE QUESTIONS?

If you have any questions about this research project, please contact: Sam Johnson. Sam.Johnson@oregonstate.edu.

If you have questions about your rights or welfare as a participant, please contact the Oregon State University Institutional Review Board (IRB) Office, at (541) 737-8008 or by email at IRB@oregonstate.edu

12. WHAT DOES MY SIGNATURE ON THIS CONSENT FORM MEAN?

Your signature indicates that this study has been explained to you, that your questions have been answered, and that you agree to take part in this study. You will receive a copy of this form.

Do not sign after the expiration date: Delete this line only if the study is exempt. The IRB will insert the appropriate date when the consent form is approved.

Participant's Name (printed): ____

______________________________________ ____________________________

(Signature of Participant) (Date)

______________________________________ ____________________________

(Signature of Person Obtaining Consent) (Date)

APPENDIX B: HEALTH HISTORY QUESTIONAIRE

Screening Questionnaire

Participant Code: ________ Date _____________

Age: ________ Sex: _____________

1. On average, how many <u>days</u> of the week do you participate in physical activity? _____

2. On average, how <u>minutes</u> do you participate in physical activity during each session? _____

3. Generally, what kinds of physical activity do normally engage in?

4. Do you currently have any injuries or illnesses that limit your ability to perform your regular physical activity? Yes No

5. Have you had any leg or low back injuries in the past 6 months? Yes No

6. Have you had surgery on your hip, knee, or ankle? Yes No

7. Have you performed any strenuous, fatiguing physical activity today? Yes No

APPENDIX C: DATA COLLECTION SHEET

Participant Code:_______ Sex:_____ Age:_______

Dominant leg:________ Height:____________cm Weight:__________kg

RTD Measurement

MG	T	Comments
HE	T1	
	T2	
	T3	
	T4	
	T5	
KE	T1	
	T2	
	T3	
	T4	
	T5	
PF	T1	
	T2	
	T3	
	T4	
	T5	

VJH

T1:__________ T2:__________ T3:__________ T4:__________ T5:_________

APPENDIX D: COUNTERBALANCE

Testing Order A	HE	KE	PF
Testing Order B	PF	HE	KE
Testing Order C	KE	PF	HE
Testing Order D	HE	PF	KE
Testing Order E	PF	KE	HE
Testing Order F	KE	HE	PF
Testing Order A	HE	KE	PF
Testing Order B	PF	HE	KE
Testing Order C	KE	PF	HE
Testing Order D	HE	PF	KE
Testing Order E	PF	KE	HE
Testing Order F	KE	HE	PF
Testing Order A	HE	KE	PF
Testing Order B	PF	HE	KE
Testing Order C	KE	PF	HE
Testing Order D	HE	PF	KE
Testing Order E	PF	KE	HE
Testing Order F	KE	HE	PF
Testing Order A	HE	KE	PF
Testing Order B	PF	HE	KE
Testing Order C	KE	PF	HE
Testing Order D	HE	PF	KE
Testing Order E	PF	KE	HE
Testing Order F	KE	HE	PF
Testing Order A	HE	KE	PF
Testing Order B	PF	HE	KE
Testing Order C	KE	PF	HE
Testing Order D	HE	PF	KE
Testing Order E	PF	KE	HE
Testing Order F	KE	HE	PF

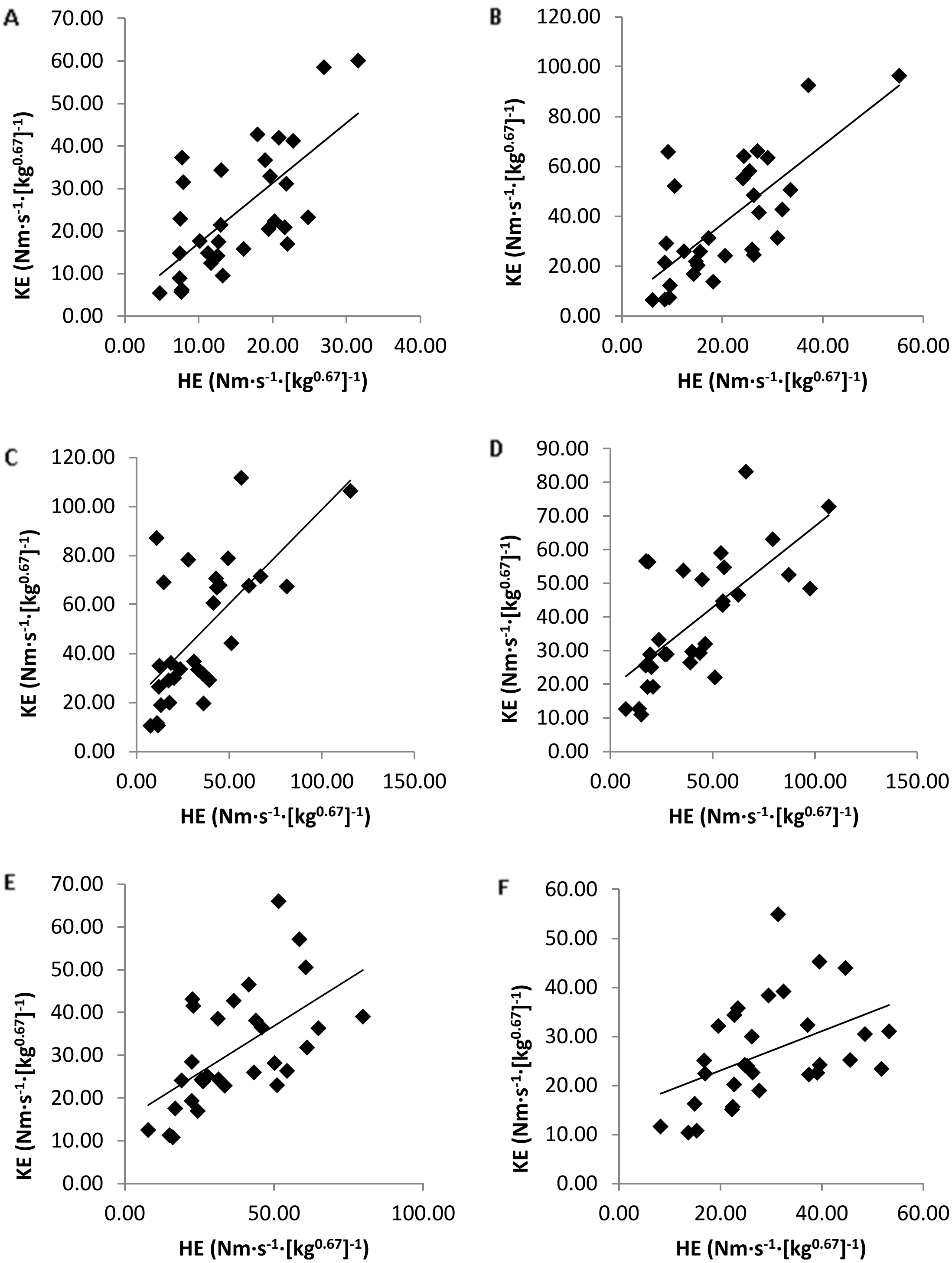
* HE = Hip Extensors, KE = Knee Extensors, PF = Plantarflexors

APPENDIX E: DATA

S	Sex	Age	Ht	BM	DL	HE RTD 25	HE RTD 50	HE RTD 100	HE RTD 150	HE RTD 200	HE RTD 250	KE RTD 25	KE RTD 50	KE RTD 100	KE RTD 150	KE RTD 200	KE RTD 250	PF RTD 25	PF RTD 50	PF RTD 100	PF RTD 150	PF RTD 200	PF RTD 250
1	M	30	1.83	82.6	R	26.95	37.12	56.54	66.26	51.56	31.38	58.55	92.50	111.70	83.19	66.01	54.95	24.07	32.79	42.47	39.73	34.01	30.18
2	M	26	1.81	75.6	L	31.60	55.22	115.44	106.72	58.54	39.55	60.12	96.36	106.38	72.85	57.11	45.28	30.58	44.11	55.22	49.92	40.40	33.26
3	M	21	1.76	72.1	R	7.92	10.47	14.68	18.68	22.68	22.74	31.53	52.12	69.01	56.38	43.10	34.39	8.64	11.42	16.91	19.11	17.11	14.46
4	M	25	1.76	77.3	L	19.68	26.24	41.51	44.84	31.17	19.58	32.91	48.46	60.61	51.11	38.53	32.16	18.97	26.67	31.33	26.86	21.89	18.85
5	F	25	1.59	58.1	R	7.43	9.55	13.20	20.87	24.43	22.27	8.92	12.26	18.94	19.28	16.95	15.15	13.54	17.07	20.67	21.23	20.41	19.24
6	M	23	1.77	73.9	R	7.51	8.81	12.35	19.40	25.76	26.35	22.89	29.13	35.00	28.93	24.29	22.65	16.07	20.05	23.84	24.52	23.28	22.39
7	M	22	1.85	91.8	R	12.56	15.06	17.27	20.04	22.46	22.43	14.22	20.36	29.00	25.06	19.31	15.67	6.66	8.82	11.49	10.88	9.22	7.94
8	M	22	1.81	74.2	R	20.27	27.29	43.34	55.64	43.92	26.18	22.31	41.50	66.87	54.77	38.13	30.01	13.77	20.56	29.95	27.88	20.78	13.70
9	M	28	1.83	85.4	R	7.76	9.17	10.89	17.47	22.94	23.45	37.30	65.78	87.10	56.64	41.53	35.80	16.74	21.51	26.22	26.07	23.11	20.76
10	M	21	1.82	65.3	R	20.86	24.26	27.97	35.70	36.55	29.51	41.96	64.15	78.26	53.83	42.74	38.37	21.71	29.69	35.53	31.07	25.39	22.26
11	M	22	1.84	69.3	R	21.87	33.57	66.96	79.31	60.65	44.66	31.18	50.59	71.44	63.13	50.54	43.98	24.36	34.98	48.43	47.58	40.83	34.67
12	M	21	1.78	74	R	10.15	12.33	18.60	23.72	22.50	16.81	17.68	25.95	36.14	33.25	28.47	25.12	8.73	10.83	12.72	12.01	10.90	9.97
13	F	23	1.75	68.7	R	11.68	14.27	17.74	18.12	16.90	14.91	12.47	16.81	19.92	19.21	17.53	16.29	8.86	9.56	10.70	10.94	10.41	10.25
14	F	20	1.62	56.6	R	4.75	6.09	7.56	7.57	7.84	8.19	5.42	6.43	10.52	12.67	12.52	11.65	4.50	5.34	6.03	5.11	4.08	3.74
15	F	23	1.65	83.5	R	12.68	15.56	23.59	27.53	27.64	25.26	17.52	25.83	33.58	28.97	25.15	24.03	14.35	17.10	18.25	15.74	13.92	13.17
16	M	26	1.75	75.8	R	13.03	24.09	81.07	97.60	64.92	48.52	34.37	55.18	67.32	48.48	36.30	30.52	21.18	30.12	39.79	35.69	27.99	23.24
17	M	26	1.87	122.7	R	22.79	29.02	42.89	55.01	50.22	37.47	41.24	63.46	70.59	44.72	28.17	22.23	12.10	15.42	17.09	14.03	10.84	9.15
18	M	24	1.73	65.1	R	17.97	26.98	49.39	54.05	41.57	32.46	42.77	66.12	78.86	59.03	46.52	39.20	12.85	20.24	32.63	34.11	29.66	25.19
19	M	21	1.86	78.5	R	12.99	17.26	31.01	46.34	54.37	51.79	21.46	31.29	36.78	32.03	26.35	23.41	16.23	22.98	29.89	27.85	23.41	20.43
20	F	20	1.67	60.2	R	19.46	25.94	39.23	39.10	31.40	24.80	20.48	26.65	29.18	26.48	24.37	24.21	15.67	21.24	28.96	27.97	24.11	21.23
21	F	21	1.67	87.6	R	22.03	26.26	35.95	43.74	43.29	39.59	17.01	24.51	31.61	29.35	25.99	24.23	10.93	14.55	18.62	18.43	16.53	14.83
22	F	23	1.69	78.8	R	18.99	25.41	44.88	62.54	61.08	45.60	36.71	58.16	67.83	46.61	31.78	25.21	15.55	20.89	25.23	21.50	17.64	15.43
23	F	22	1.69	62	R	7.44	8.52	12.06	17.26	19.04	17.00	14.81	21.46	26.36	25.58	24.10	22.44	11.19	13.30	16.82	17.58	16.41	14.71
24	F	21	1.62	59.2	R	21.63	30.95	51.20	54.90	45.93	37.21	20.93	31.34	44.16	43.57	36.48	32.35	11.09	14.33	19.68	20.94	19.95	18.49
25	F	23	1.62	53.8	R	11.26	14.71	20.22	26.71	26.25	22.71	14.83	21.91	29.94	28.90	23.88	20.23	16.37	21.38	26.37	25.57	23.76	21.96
26	F	22	1.77	69.1	R	24.81	31.94	60.65	87.21	79.81	53.27	23.27	42.73	67.62	52.57	39.03	31.08	21.62	29.51	37.94	35.16	29.35	25.05
27	F	23	1.73	68.6	R	13.24	18.17	36.16	51.10	51.05	39.09	9.55	13.78	19.59	22.07	22.99	22.61	12.74	15.70	18.84	18.02	15.59	14.21
28	F	20	1.57	65.1	R	7.65	8.51	11.58	15.13	16.08	15.32	5.71	6.61	10.60	11.00	10.80	10.80	8.36	10.15	10.93	10.06	8.86	8.02
29	F	20	1.52	52.7	R	16.08	20.54	33.27	39.99	33.49	27.68	15.81	24.16	33.38	29.71	22.86	18.97	10.79	13.81	16.91	16.29	14.08	12.12
30	F	22	1.64	57.7	R	7.73	9.43	11.05	14.10	14.99	13.70	6.18	7.42	11.61	12.69	11.27	10.39	8.32	9.86	10.73	10.22	9.35	8.64

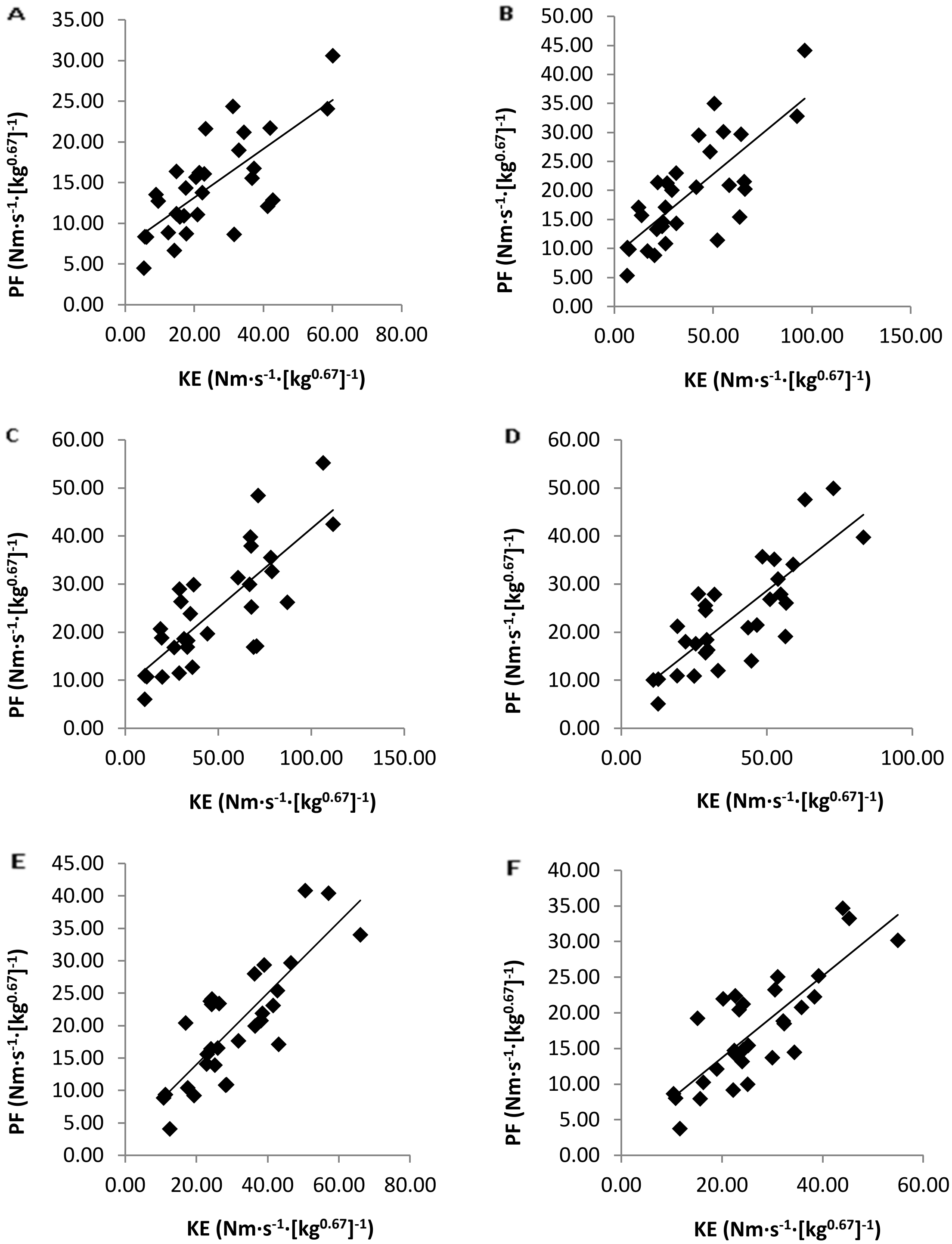
* S = Subject, Ht = Height (m), BM = Body mass (kg), DL = Dominant leg, RTD = Rate of torque development, HE = Hip extensors, KE = Knee extensors, PF = Plantarflexors

APPENDIX F: SCATTERPLOTS OF HE RTD VS. KE RTD



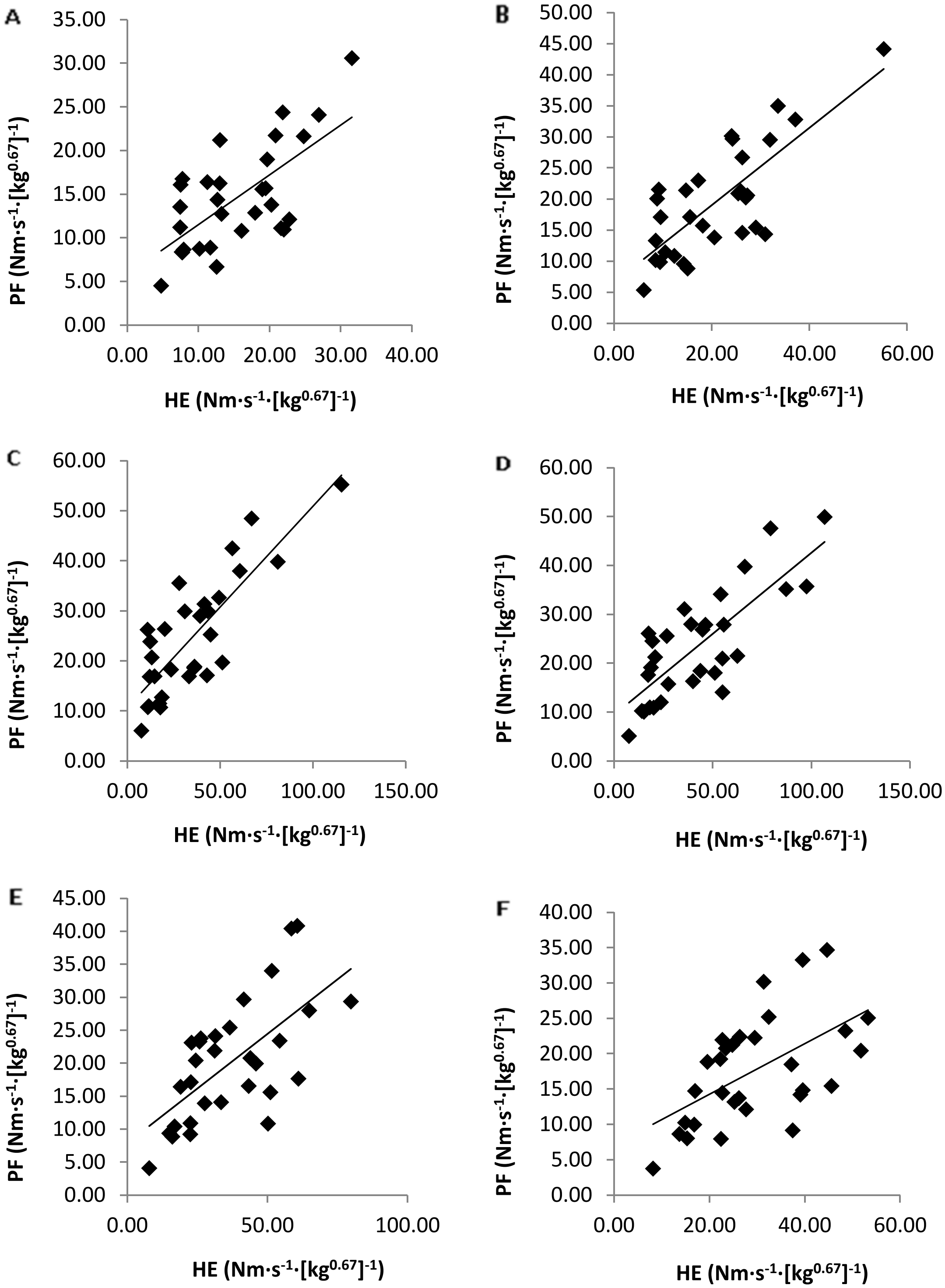
Scatterplots of RTD between the hip extensors (HE) and the knee extensors (KE) at A) 0-25 ms, B) 0-50 ms, C) 0-100 ms, D) 0-150 ms, E) 0-200 ms, and F) 0-250 ms.

APPENDIX G: SCATTERPLOTS OF KE RTD VS. PF RTD



Scatterplots of RTD between the knee extensors (KE) and the plantarflexors (PF) at A) 0-25 ms, B) 0-50 ms, C) 0-100 ms, D) 0-150 ms, E) 0-200 ms, and F) 0-250 ms.

APPENDIX H: SCATTERPLOTS OF HE RTD VS. PF RTD



Scatterplots of RTD between the hip extensors (HE) and the plantarflexors (PF) at A) 0-25 ms, B) 0-50 ms, C) 0-100 ms, D) 0-150 ms, E) 0-200 ms, and F) 0-250 ms.