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Slope of the Torque-Velocity Relationship Between Males and Females

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By

Robert Bromen

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Master of Science

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Robert Bromen

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Abstract

The purpose of this study was to explore potential sex-specific differences in the torque-velocity relationship of the quadriceps and hamstrings. Sixteen male and 10 female recreationally active college students participated in the study. Concentric and eccentric peak torque was measured on a Biodex System 4 Pro at 60, 120, 180 and 240 °/s along with isometric peak torque at a knee angle of 60° (0° = full extension). Peak torque was then normalized to lean body mass as determined by hydrostatic weighing. The rate of change in peak torque as movement velocity increases was then analyzed for differences between sexes. The main finding of this study is that after normalizing peak torque to lean body mass there was no sex by velocity interaction ($p > 0.05$) for concentric muscle actions of the quadriceps, or for concentric and eccentric muscle actions of the hamstrings. However, there was a significant sex by velocity interaction for eccentric muscle actions of the quadriceps ($p < 0.05$, $\eta^2 = 0.358$). Peak torque normalized to lean body mass accounts for many of the reported differences between sexes in peak torque and the rate of change in peak torque as movement velocity increases in the quadriceps and hamstrings. However, some sex-specific differences remain that result in a difference in the slope of the torque-velocity relationship between sexes for eccentric muscle actions of the quadriceps.

Keywords: torque-velocity relationship, sex differences, isokinetic, lean body mass

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Next, I would like to thank Dr. Dave Suprak for his assistance and patience as well. His feedback and help were critical in the development of my research methods and data analysis. I am incredibly grateful for all the support he has provided as I attempted to figure out how to do what I needed to do. I will always appreciate his door having been open when I needed him.

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Manuscript

Introduction

The inverse relationship between muscle force and velocity was potentially first referenced by Hill in 1922 (Hill, 1922), and in 1935, Fenn and Marsh (1935) conducted the first study of the force-velocity (F-V) relationship which was later outlined by Hill in his influential 1938 paper (Hill, 1938). However, *in* vivo studies would not take place until 1947 for the concentric F-V relationship (Dern et al., 1947) and 1973 for the eccentric F-V relationship (Komi, 1973). In the nearly 90 years that the F-V relationship has been investigated, numerous studies have examined how movement velocity affects muscle force both concentrically and eccentrically, although relatively little attention has been given to the actual shape of the F-V relationship (Alcazar et al., 2019). Since Hill's paper in 1938 (Hill, 1938), the shape of the concentric F-V relationship has been proposed to be hyperbolic (Hill, 1938), double hyperbolic (Edman, 1988), and linear (Bobbert, 2012). Regarding the eccentric F-V relationship, it is now generally accepted that maximal voluntary eccentric muscle actions can produce forces greater than isometric muscle actions (Alcazar et al., 2019; Hahn, 2018; Herzog, 2018), however, defining the eccentric F-V relationship may be complicated by a leveling off of forces that seems to happen as movement velocity increases, although the exact point at which this happens has not been established (Dudley et al., 1990; Hahn et al., 2014; Holder-Powell & Rutherford, 1999). Possibly due to these findings, attempts to define equations for the lesser studied eccentric F-V relationship have only applied up to a certain amount of force (Mashima et al., 1972) or within a specific range of movement velocity (Cole et al., 1996).

As the shape of the F-V relationship continues to be studied, an area that warrants further investigation is potential differences in the slope, or rate of change, of the F-V relationship (or more accurately, the torque velocity (T-V) relationship) between males and females. Potential differences between sexes in the T-V relationship may indicate a need to take sex into account when designing resistance training and rehabilitation protocols. Searches for studies comparing the T-V relationship between sexes yielded few results with even fewer studies specifically examining the slope of the T-V relationship. Although there is evidence of potential differences between sexes in torque production via concentric and eccentric muscle actions, it is not clear if these differences affect the slope of the T-V relationship.

While multiple authors have reported greater peak torque (PT) in males compared to females, even when normalized to muscle cross sectional area (Bagley et al., 2021; Kanehisa et al., 1996) or body mass (Anderson et al., 2001; Colliander & Tesch, 1991; Highgenboten et al., 1988; Lephart et al., 2002; Lisee et al., 2019; Miller et al., 1993; Pincivero et al., 2004; Pincivero, Dixon, et al., 2003; Stock et al., 2013), this is not always the case (Heyward et al., 1986; Kong & Burns, 2010; Neder, Nery, Shinzato, et al., 1999; Neder, Nery, Silva, et al., 1999; Schantz et al., 1983) nor does greater PT at various movement velocities necessarily mean a difference in the rate of change in muscle torque as velocity increases. There may also be a potential difference in the ratio of eccentric to concentric PT where authors reported both lower (Mark De Ste Croix et al., 2007) and higher (Colliander & Tesch, 1989; Griffin et al., 1993; Seger & Thorstensson, 1994) eccentric relative to concentric PT in females compared to males. The reason for this difference was contrastingly reported to be due to a lower ability to produce concentric torque in females rather than greater eccentric torque (Mark De Ste Croix et al., 2007) and the opposite of a greater ability to produce eccentric torque in females compared to males (Griffin et al., 1993). Again though, this does not necessarily mean a difference in the slope of the T-V relationship within a specific type of muscle action.

Even when examining the rate of change in PT as movement velocity increases, it is not clear if there is a difference between sexes. Some researchers reported a greater decrease in concentric PT in females compared to males as movement velocity increases (Evetovich et al., 1998; Froese & Houston, 1985; Griffin et al., 1993; Seger & Thorstensson, 1994; Wagner et al., 1992), although this difference may only be measured when comparing absolute torques and may not exist after normalizing torques to body mass (Colliander & Tesch, 1989, 1991; Kong & Burns, 2010). Compared to concentric muscle actions, eccentric torque seems to have less variability in the reported results with PT, generally not changing significantly in either males or females as movement velocity increases (Carney et al., 2012; Cramer et al., 2002; Evetovich et al., 1998; Griffin et al., 1993; Seger & Thorstensson, 1994). Although increases in eccentric PT in females (Colliander & Tesch, 1989) along with decreases in PT in males (Colliander & Tesch, 1989, 1991) as movement velocity increases have also been reported. Despite these reported differences in the rate of change in concentric torques as movement velocity increases, in studies where the slope of the T-V relationship was compared between sexes the researchers consistently reported no differences between sexes in the rate of change in PT (Carney et al., 2012; De Koning et al., 1985; Froese & Houston, 1985; Otis & Godbold, 1983; Seger & Thorstensson, 1994). However, the method used to compare slopes was not reported by the authors of most studies (Carney et al., 2012; Froese & Houston, 1985; Seger & Thorstensson, 1994) with only one (De Koning et al., 1985) that reported using Hill's equation (Hill, 1938) and another compared linear regression lines (Otis & Godbold, 1983). Of the studies that examined the eccentric T-V relationship, the researchers did not report how the slope was compared between sexes in either of these studies (Carney et al., 2012; Seger & Thorstensson, 1994). Additionally, all the studies that compared the slope of the T-V relationship between sexes utilized absolute torques which cannot account for differences in body mass, particularly lean body mass (LBM), between subjects that may affect the results. As such, further research comparing the slope of the T-V relationship between sexes utilizing normalization methods that allow for better comparisons of PT between subjects of different sizes and differing amounts of muscle mass should be conducted to better elucidate any potential sex-specific differences in the T-V relationship. Therefore, the purpose of this study is to measure PT of the knee extensors and flexors throughout the T-V relationship in both males and females while normalizing PT to LBM to compare the slope of the T-V relationship. We hypothesize that after normalizing PT to LBM there will be no difference between sexes in PT or the rate of change in PT as movement velocity increases.

Methods

Subject Characteristics

Twenty-six (16 males, 10 females) subjects who exercised at least three times per week for 30 minutes or more (De Marche Baldon et al., 2011; Kong & Burns, 2010; Pincivero, Dixon, et al., 2003) were recruited from the university's Kinesiology program. Subjects were free from any current lower-extremity injuries (De Marche Baldon et al., 2011; Griffin et al., 1993), had no lower-extremity injuries in the last 12 months (Burfeind et al., 2012), no pain when producing leg muscle forces (Kong & Burns, 2010; Shih et al., 2021), had no history of surgery to the lower extremities (De Marche Baldon et al., 2011; Highgenboten et al., 1988; Lisee et al., 2019), and had no known cardiovascular or neurological problems that limited physical activity (Claiborne et al., 2006; De Marche Baldon et al., 2011; Griffin et al., 1993). The research procedures were explained and written informed consent was obtained from all subjects. Research procedures were approved by the Western Washington University institutional review board.

Experimental Procedures

Subjects were instructed to avoid strenuous exercise for 48 hours prior to the data collection (De Araujo Ribeiro Alvares et al., 2015; Sole et al., 2007), to avoid stimulants (e.g. caffeine) or depressants (e.g. alcohol) for 24 hours before the data collection (Brown et al., 1995; Cicone et al., 2021; Nickerson et al., 2017), and not to eat or drink anything other than water for three hours before the data collection (Houska et al., 2018; Nickerson et al., 2017). Leg dominance was determined by asking each subject which leg they would kick a ball with and having the subject kick a ball if they were unsure, with the kicking leg determined to be the dominant leg (De Marche Baldon et al., 2011; Mark De Ste Croix et al., 2007; Sole et al., 2007). Prior to testing, subjects performed a five-minute warm-up on a cycle ergometer (Monark 828E, Monark Exercise AB, Vansbro, Sweden) at 25 watts (Brown et al., 1995; Gomes et al., 2021).

Testing for isokinetic and isometric variables used a Biodex System 4 Pro (Biodex Medical, Inc., Shirley, NY). Subjects were seated on the Biodex chair and secured via torso, pelvis, and thigh straps to prevent any extraneous movement (Lephart et al., 2002; Pincivero et al., 2000, 2004) and were instructed to fold their arms across their chest during the testing procedure (Lephart et al., 2002; Pincivero et al., 2000; Pincivero, Gandaio, et al., 2003). The axis of rotation of the dynamometer was aligned with the lateral epicondyle of the femur (Mark De Ste Croix et al., 2007; Lephart et al., 2002; Pincivero et al., 2000, 2004). A strap securing the shank to the dynamometer lever arm was fastened 2-3 cm superior to the medial malleolus (Alt et al., 2018; Mark De Ste Croix et al., 2007; Sole et al., 2007). Gravity correction was performed with the knee in a relaxed state at terminal extension (Bottaro et al., 2005; Pincivero et al., 2000, 2004). The range of motion during isokinetic testing was from 90° to 10° of knee flexion (0° = full extension) (De Araujo Ribeiro Alvares et al., 2015; Grbic et al., 2017; Janicijevic et al., 2019; Rezaei et al., 2014). Peak torque as reported by the dynamometer software (Advantage BX v5.202, Biodex Medical System, Shirley, NY, USA) was later used during statistical analysis in SPSS (Botton et al., 2016; Kong & Burns, 2010). Calibration of the Biodex dynamometer was performed prior to testing each subject according to the procedures specified by the manufacturer (*System 4 (Advantage BX Software 5.2X)*, 2021).

Testing order was randomized between isometric, concentric, and eccentric muscle actions and also randomized for velocity within conditions (Bagley et al., 2021; Carney et al., 2012; De Marche Baldon et al., 2011; Froese & Houston, 1985; Seger & Thorstensson, 1994; Timm & Fyke, 1993). Subjects performed reciprocal knee extension and flexion for one set of five repetitions (Blazquez et al., 2013; Carney et al., 2012; Dorgo et al., 2012; Timm & Fyke, 1993) per velocity at 60, 120, 180, and 240 degrees per second (°/s) with 60 seconds of rest between velocities (Bagley et al., 2021; Blazquez et al., 2013; Froese & Houston, 1985). Prior to testing at each velocity, three submaximal repetitions were conducted for familiarization (Cramer et al., 2002; Siqueira et al., 2002). Isometric testing consisted of three, five-second (Bagley et al., 2021; Krishnan & Williams, 2014; Pincivero et al., 2004; Šarabon et al., 2021) reciprocal contractions of knee extension and flexion at 60° (De Araujo Ribeiro Alvares et al., 2015; Krishnan & Williams, 2014; Šarabon et al., 2021) of knee flexion (0° = full extension) with 60 seconds of rest between repetitions (Bagley et al., 2021; Gomes et al., 2021; Šarabon et al., 2021). For all test sets, subjects were instructed to give a maximal effort and were provided with verbal encouragement along with visual feedback from the Biodex monitor to help achieve maximal voluntary effort (Claiborne et al., 2006; Mark De Ste Croix et al., 2007; Pincivero, Campy, et al., 2003).

Following the testing protocol on the Biodex, hydrostatic weighing was conducted to determine LBM. Immediately prior to the hydrostatic weighing protocol, subjects were instructed to use the restroom and void the bladder and bowels if possible (Houska et al., 2018; Thomas & Etheridge, 1980). Body mass in air was obtained with a beam balance scale (Katch et al., 1967) accurate to 113 grams. Vital capacity was measured on a Pneumoscan S-301B spirometer (Vacu-Med, Ventura, CA, USA) with the highest of three trials used to calculate residual lung volume (RV) by multiplying vital capacity by 0.24 for males and 0.28 for females (Wilmore, 1969). Underwater weighing trials were conducted in a large water tank approximately 2.23 x 0.86 x 0.76 meters with subjects submerged in the prone position (Katch et al., 1967; Thomas & Etheridge, 1980) while lying on a metal frame suspended by two cables to a Chatillon hanging scale (AMETEK STC, Largo, FL, USA) accurate to 20 grams (Thomas & Etheridge, 1980). Subjects were instructed to remove any air trapped in their hair or swimsuit prior to weighing (Gibby et al., 2017; Wells et al., 2020). Subjects were told to exhale as much air as possible once submerging under water and when all air was expired underwater mass was recorded (Gibby et al., 2017; Nickerson et al., 2017; Wells et al., 2020). Water temperature was measured every trial with water density adjusted based on temperature (Ward et al., 1978; Wells et al., 2020). Six to ten trials (Cicone et al., 2021; Nickerson et al., 2017; Ward et al., 1978) were conducted and the average of the highest three trials used for calculations of body volume (Cicone et al., 2021; Nickerson et al., 2017). Gastrointestinal gas volume was assumed to be 100 ml for calculations of body density (Levitt, 1971; Wells et al., 2020). Archimedes Principle was utilized to calculate body volume with net under water weight divided by water density after a correction for RV along with gastrointestinal gas volume (Gibby et al., 2017; Houska et al., 2018). Body density was then determined by dividing body mass in air by body volume with body density then converted into percent body fat (%BF) using the Siri equation (Gibby et al., 2017; Houska et al., 2018; Siri, 1956).

Statistical Analysis

For comparison of torques between sexes, two-way mixed ANOVAs were performed for concentric and eccentric muscle actions of each muscle group with between factor sex and within factor isokinetic velocity. If significant sex by velocity interactions were found, simple effects analyses were conducted to determine which conditions had significant differences. An independent t-test was also done to assess differences between sexes in isometric torques. The significance level was set at $p < 0.05$ for all tests. Effect size for each ANOVA was determined using partial eta squared (η^2) with effect sizes classified as small (0.01), medium (0.06) and large (0.14) (Stock et al., 2013). The effect size for independent t-tests was determined by Cohen's *d* with effect sizes classified as small (0.2), medium (0.5), and large (≥ 0.8) (Sullivan & Feinn, 2012). Statistical analysis was performed using SPSS version 28 (IBM, Armonk, NY, USA).

Results

Subject characteristics are presented in Table 1. When examining the rate of change in PT as movement velocity increases, there was no significant sex by velocity interaction for concentric muscle actions of the quadriceps or for concentric and eccentric muscle actions of the hamstrings ($p > 0.05$, η^2 0.17 - 0.26). The only significant sex by velocity interaction was for eccentric muscle actions of the quadriceps ($p < 0.05$, $\eta^2 = 0.358$). When PT for both sexes is plotted, the similarities in the rate of change in quadriceps and hamstrings PT as movement velocity increases during concentric muscle actions is evident (Figures 1 and 2). The discrepancy between sexes in eccentric PT of the quadriceps as movement velocity increases can be seen in Figure 3. The relatively constant eccentric PT in the hamstrings for both sexes can also be observed in Figure 4. An overall view of the full T-V relationship measured in the study is presented in Figures 5 and 6 for easy comparison of all measured PTs.

Absolute PT was greater (p = 0.002 to < 0.001, d = 1.46 - 3.03) in males than females for all muscle actions and movement velocities in both the quadriceps and hamstrings (Tables 2 and 3). After normalizing PT to LBM, PT was not significantly different between sexes in the quadriceps during concentric muscle actions (all velocities), however, males produced significantly greater PT during eccentric muscle actions at 60 (p = 0.017, d = 1.03) and 120 (p = 0.46, d = .992) °/s but not 180 or 240 °/s (Table 4). For the hamstrings, PT was similar between males and females at all velocities for both concentric and eccentric muscle actions (Table 5). Isometric PT was not significantly different between sexes for the quadriceps (Table 4) but was significantly greater (p = 0.021, d = 1.0) in males than females in the hamstrings (Table 5).

Table 1

Subject Characteristics

	Age (yrs)	Height (m)	Mass (kg)	LBM (kg)	FM (kg)	% BF
Males	21.1 ± 1.8	1.8 ± 0.1	77.0 ± 8.3	65.0 ± 6.9	12.0 ± 4.9	15.5 ± 4.9
Females	21.1 ± 1.5	1.7 ± 0.1	67.1 ± 14.8	49.8 ± 6.8	17.4 ± 9.0	24.7 ± 6.7

Note: Average ± standard deviation for all subject characteristics; Mass - body mass in air, LBM - lean body mass, FM - fat mass, % BF - body fat percentage

Table 2

Quadriceps Absolute Peak Torque

	Males	Females
Concentric		
°/s	PT (Nm)	PT (Nm)
60	229.29* ± 34.85	155.66 ± 42.47
120	198.05* ± 28.01	131.95 ± 34.00
180	165.64* ± 19.53	111.12 ± 30.12
240	152.16* ± 21.86	98.60 ± 27.41
Isometric		
0	259.44* ± 39.17	180.80 ± 57.94
Eccentric		
-60	278.73* ± 63.26	168.62 ± 51.62
-120	268.56* ± 49.34	163.01 ± 54.97
-180	254.36* ± 54.48	175.31 ± 53.22
-240	254.14* ± 57.36	170.60 ± 55.66

Note: * indicates significant difference between sexes

Table 3

Hamstrings Absolute Peak Torque

	Males	Females
Concentric		
°/s	PT (Nm)	PT (Nm)
60	119.78* ± 23.25	72.88 ± 15.61
120	109.90* ± 16.63	64.90 ± 11.29
180	98.10* ± 15.12	55.83 ± 11.93
240	86.44* ± 13.74	50.00 ± 11.38
Isometric		
0	140.05* ± 20.27	90.20 ± 22.31
Eccentric		
-60	217.18* ± 35.34	139.82 ± 23.69
-120	213.14* ± 31.68	131.76 ± 28.96
-180	209.73* ± 27.27	136.20 ± 25.04
-240	208.41* ± 29.34	135.08 ± 26.78

Note: * indicates significant difference between sexes

Table 4

Quadriceps Adjusted Peak Torque

	Males	Females
Concentric		
°/s	PT (Nm/kg)	PT (Nm/kg)
60	3.54 ± 0.46	3.12 ± 0.71
120	3.05 ± 0.32	2.63 ± 0.56
180	2.54 ± 0.21	2.22 ± 0.56
240	2.32 ± 0.23	2.01 ± 0.52
Isometric		
0	4.01 ± 0.53	3.59 ± 0.95
Eccentric		
-60	4.28* ± 0.76	3.39 ± 0.99
-120	4.15* ± 0.68	3.29 ± 1.11
-180	3.93 ± 0.77	3.54 ± 1.06
-240	3.91 ± 0.80	3.47 ± 1.17

Note: Quadriceps peak torque adjusted based on lean body mass; * indicates significant difference between sexes

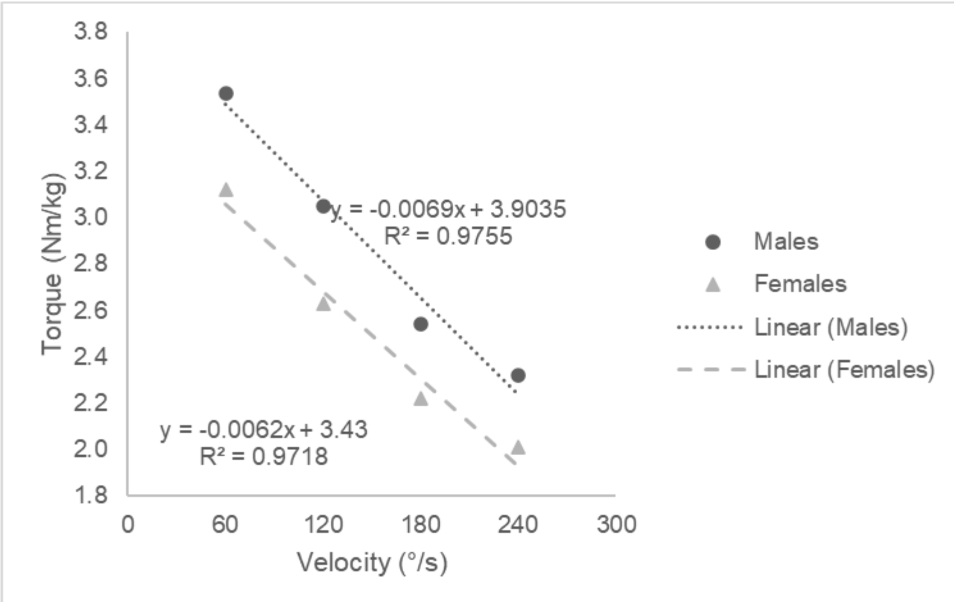
Table 5

Hamstrings Adjusted Peak Torque

	Males	Females
Concentric		
°/s	PT (Nm/kg)	PT (Nm/kg)
60	1.86 ± 0.37	1.48 ± 0.27
120	1.69 ± 0.23	1.31 ± 0.25
180	1.54 ± 0.28	1.12 ± 0.25
240	1.34 ± 0.20	1.04 ± 0.29
Isometric		
0	2.16* ± 0.31	1.82 ± 0.38
Eccentric		
-60	3.34 ± 0.49	2.81 ± 0.40
-120	3.31 ± 0.52	2.67 ± 0.50
-180	3.23 ± 0.43	2.74 ± 0.44
-240	3.22 ± 0.44	2.74 ± 0.54

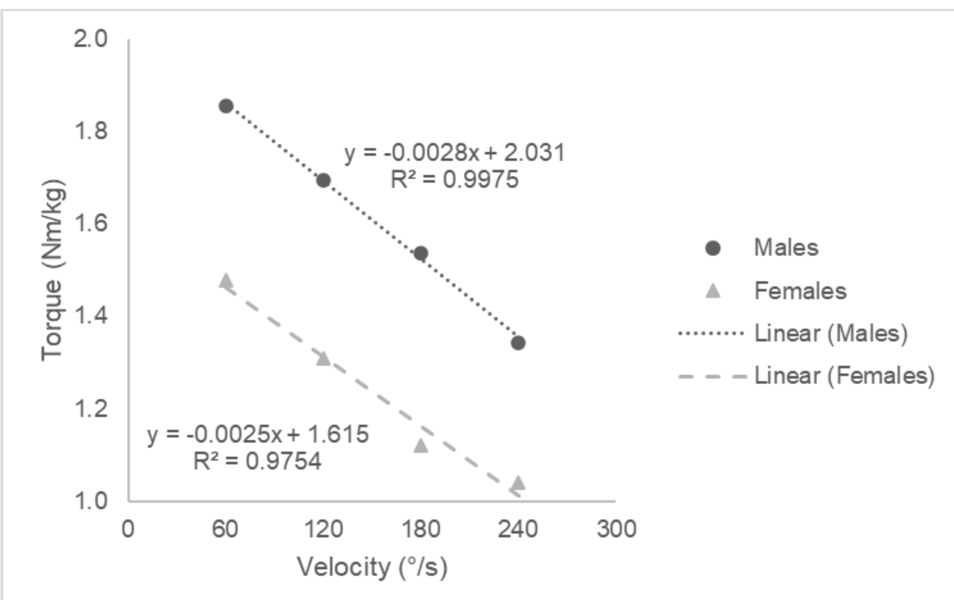
Note: Hamstrings peak torque adjusted based on lean body mass; * indicates significant difference between sexes

Figure 1
Quadriceps Concentric Peak Torques



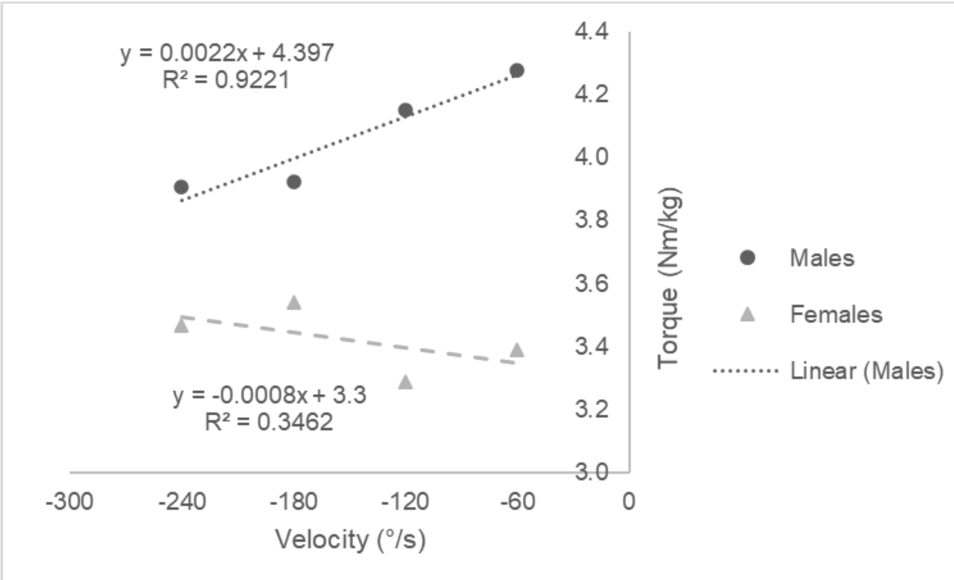
Note: Adjusted peak torque for concentric quadriceps muscle actions

Figure 2
Hamstrings Concentric Peak Torques



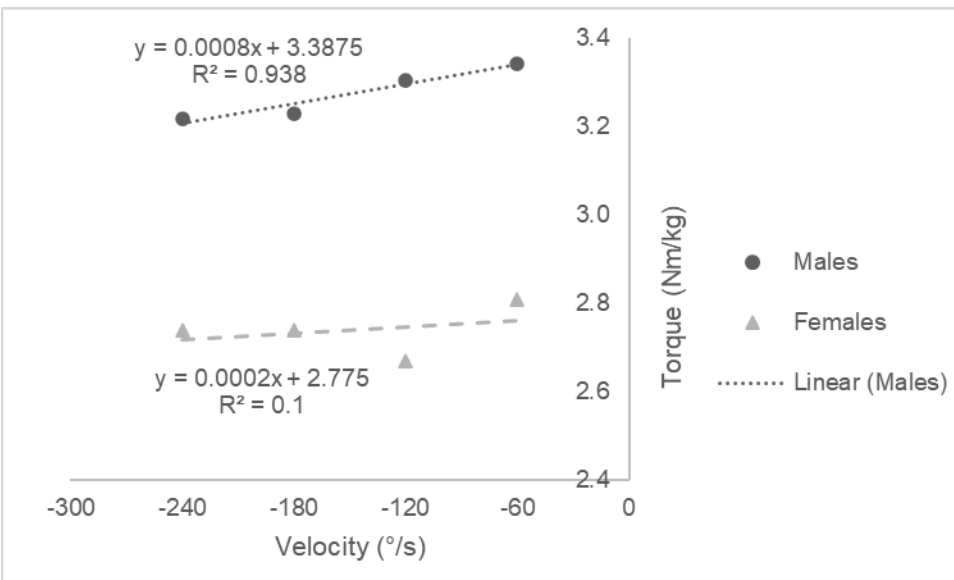
Note: Adjusted peak torque for concentric hamstrings muscle actions

Figure 3
Quadriceps Eccentric Peak Torques



Note: Adjusted peak torque for eccentric quadriceps muscle actions

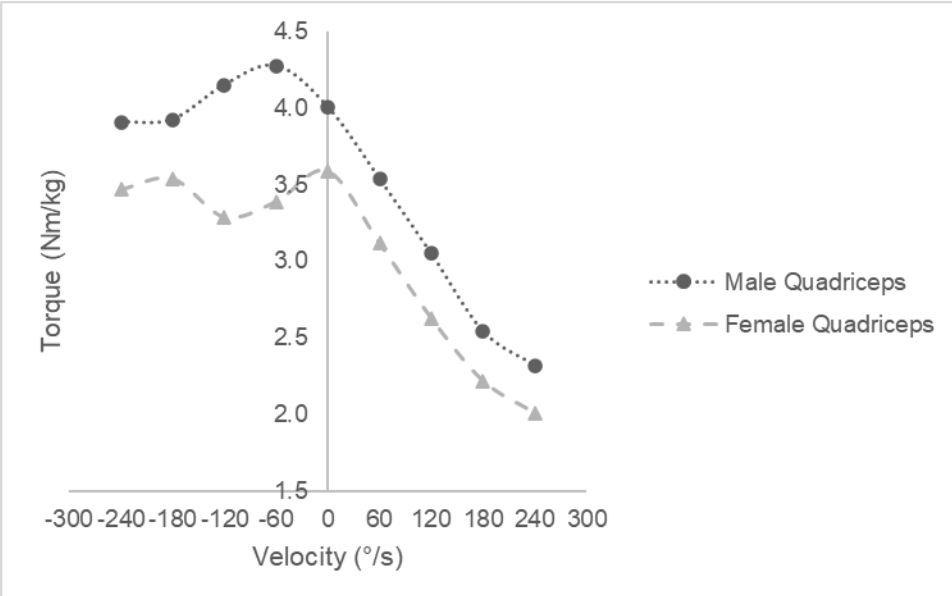
Figure 4
Hamstrings Eccentric Peak Torques



Note: Adjusted peak torque for eccentric hamstrings muscle actions

Figure 5

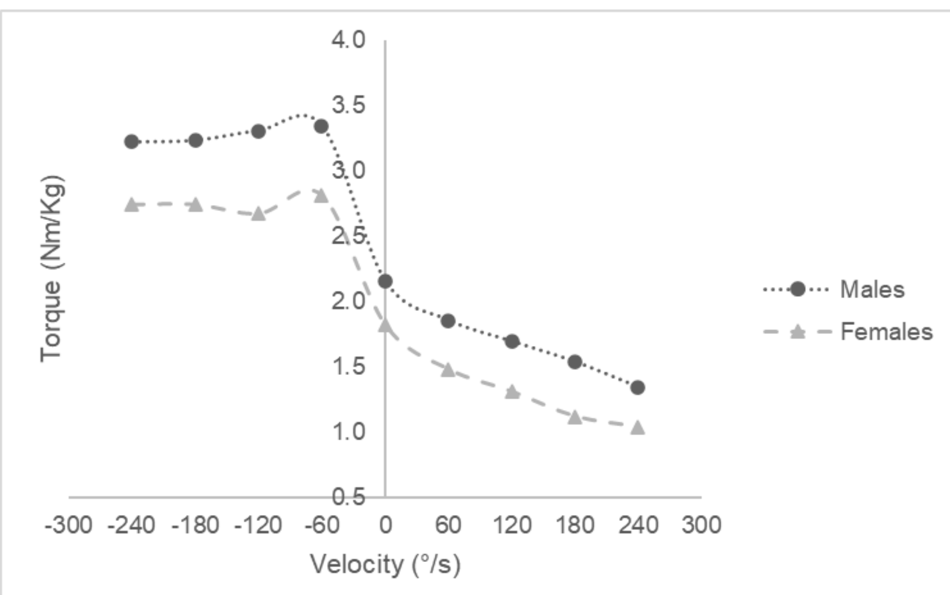
Quadriceps Full Torque-Velocity Relationship



Note: Full concentric, isometric, and eccentric torque-velocity relationship for the quadriceps

Figure 6

Hamstrings Full Torque-Velocity Relationship



Note: Full concentric, isometric, and eccentric torque-velocity relationship for the hamstrings

Discussion

The purpose of the present study was to evaluate potential sex-specific differences in the T-V relationship after normalizing PT to LBM to account for differences between subjects. This was done to determine if the rate of change in PT differs between sexes as movement velocity increases after accounting for differences in LBM between subjects, and whether this results in a different slope of the T-V relationship for each sex. The main finding of this study is that after normalizing PT to LBM there was no sex by velocity interaction for concentric muscle actions of the quadriceps, or for concentric and eccentric muscle actions of the hamstrings. However, there was a significant sex by velocity interaction for eccentric muscle actions of the quadriceps.

The lack of any significant interaction between sex and velocity in the effect on PT results in the slope of the T-V relationship between sexes being similar for concentric muscle actions of the quadriceps and hamstrings along with eccentric muscle actions of the hamstrings (Tables 4 and 5, Figures 1, 3, and 4). Although PT was not normalized in their studies, multiple researchers also reported similar slopes in the concentric T-V relationship between sexes for the quadriceps (Froese & Houston, 1985; Seger & Thorstensson, 1994), elbow flexors (De Koning et al., 1985; Otis & Godbold, 1983), and elbow extensors (Otis & Godbold, 1983). The difference between sexes in eccentric PT of the quadriceps at 60 and 120 °/s but not 180 or 240 °/s, however, results in the slope of the T-V relationship being different for each sex (Table 4, Figure 2).

These results agree with others who reported no significant differences between sexes in the rate of change in concentric PT for the quadriceps (Bagley et al., 2021; Kong & Burns, 2010; Wyatt & Edwards, 1981) or hamstrings (Wyatt & Edwards, 1981). Although none of these researchers reported on the effect of this difference on the slope of the T-V relationship. The present study's results disagree with those by previous researchers who reported a greater decrease in concentric PT as movement velocity increased in females compared to males for the quadriceps (Evetovich et al., 1998; Froese & Houston, 1985; Griffin et al., 1993; Seger & Thorstensson, 1994; Wagner et al., 1992) and hamstrings (Wagner et al., 1992). However, it is not clear how Seger and Thorstensson (1994) and Froese and Houston (1985) both reported similar slopes between sexes in the T-V relationship and a greater decrease in PT in females relative to males as movement velocity increased. It is possible that the difference in the rate of change in PT was not enough to significantly affect the overall slope of the T-V relationship across all the measured velocities.

Regarding the eccentric portion of the T-V relationship, the current study's results disagree with previous researchers who found no difference between sexes in eccentric PT of the quadriceps as movement velocity increased (Colliander & Tesch, 1989; Cramer et al., 2002; Evetovich et al., 1998; Seger & Thorstensson, 1994). A difference in the change in eccentric quadriceps PT was also reported by Colliander and Tesch (1989) who reported a decrease in PT in males as movement velocity increased from 30 to 150 °/s while PT increased in females. This is similar to the present study where PT in males decreased from 60 to 180 °/s. While eccentric quadriceps PT was significantly greater in males at the two lowest movement velocities (60 and 120 °/s), at the two higher velocities (180 and 240 °/s) PT was similar between sexes with PT not changing significantly in females as movement velocity increased. The difference between sexes reported by Colliander and Tesch (1989) in eccentric PT of the hamstrings where PT increased in females but stayed the same for males was not evident in the present study where PT did not change significantly for either sex as movement velocity increased. These results indicate that any potential sex-specific differences in the T-V relationship may be dependent on the muscle group and muscle action being studied.

It is unclear why eccentric PT was different between sexes in the quadriceps but not the hamstrings or why isometric PT was greater in males for the hamstrings but not the quadriceps. With strength relative to muscle cross sectional area often reported as similar between sexes (Castro et al., 1995; Hicks et al., 2016; Ikai & Fukunaga, 1968; Schantz et al., 1983), this difference may be related to other factors. Previous researchers have suggested maximal eccentric torque production may be limited by a neural inhibitory mechanism designed to protect the joint and surrounding tissues from injury (Westing et al., 1990), however, the results of the current study would require that mechanism to function differently not just between sexes but also based on the muscle group. It is possible that differences between sexes in the percentage of muscle fiber types (Fournier et al., 2022; Staron et al., 2000), pennation angle (Kawakami et al., 2006), and musculotendinous stiffness (Costa et al., 2012) may also affect PT for all muscle actions. However, if this is the case, then why a difference between sexes was only measured in eccentric quadriceps PT and in a maximum voluntary isometric contraction (MVIC) of the hamstrings is unknown.

Another possibility to consider is the familiarization protocol that was used. As all subjects completed the same protocol, it would seem unlikely that one sex would be affected by the familiarization protocol differently. However, the potential that females may have difficulty with isokinetic tasks and need more familiarization has been reported (Warren, 2007). The possibility that four sessions with the dynamometer may be necessary to reach a true eccentric PT (Hahn, 2018) combined with greater difficulty with isokinetic tasks may have contributed to the difference in eccentric PT for the quadriceps between sexes. It seems unlikely this difference would affect only one muscle group for a specific muscle action.

The range of movement velocities utilized in the present study should also be considered. With no significant differences between sexes in concentric torques of the quadriceps and hamstrings or in eccentric torque of the hamstrings, it is possible that no sex-specific differences exist for many muscle groups and muscle actions when measuring movement velocities within the middle of the T-V relationship. In the present study, neither extremely low nor high movement velocities were measured. With a double-hyperbolic curve reported in the T-V relationship within the high-force/low-velocity region (above about 75-80% of MVIC) (Alcazar et al., 2019; Edman, 1988; Harris & Dudley, 1994; Seger & Thorstensson, 2000) along with deviations from Hill's (1938) rectangular hyperbola in the low-force/high-velocity region (below about 40% of MVIC) (Close & Luff, 1974; Josephson & Edman, 1988; Julian et al., 1986), it is unknown if these deviations may vary between sexes. Studies measuring concentric PT within these extremes may illuminate sex-specific differences within the T-V relationship that are not measured at more moderate movement velocities. Measuring slower velocities may also be beneficial for better understanding any potential differences between sexes in the eccentric T-V relationship. Eccentric torques are often reported to not change significantly as movement velocity increases (Cramer et al., 2002; Dudley et al., 1990; Evetovich et al., 1998; Griffin et al., 1993; Seger & Thorstensson, 1994). However, it is possible that any significant increases in eccentric PT with a change in movement velocity occurs at velocities below those which are commonly studied and may plateau as low as 30 °/s (Holder-Powell & Rutherford, 1999). If that is true, then understanding if differences in the eccentric T-V relationship exist between sexes would require determining when the plateau in eccentric PT begins and measuring movement velocities under that plateau.

While not a focus of this study, both conventional and functional hamstring to quadriceps (H:Q) ratios seem to diverge from results reported by other researchers, both in the expected H:Q ratio as well as in regards to sex differences as movement velocity increases (M. De Ste Croix et al., 2007, 2017; Hewett et al., 2008; Westing & Seger, 1989). Further studies are recommended to understand these potential differences.

Limitations

There were several limitations to this study. First, the uneven number of subjects between sexes, total number of subjects, and use of only college students as subjects may limit the results of the study. Second, to increase the number of subjects, training status was not narrowly restricted. Subjects were accepted into the study if they were physically active three or more times a week with the type and duration of exercise a subject regularly participated was not controlled. Utilizing only subjects who do not engage in resistance training or who have been engaging in regular resistance training for several months may provide a better comparison in PT between sexes. Third, familiarization with the isokinetic testing protocol was only done at the time of testing. While it increases the burden on both subjects and researchers, having subjects come in for multiple familiarization sessions instead may have helped subjects to produce greater PTs, particularly for eccentric muscle actions (Hahn, 2018). Fourth, only relatively moderate movement velocities (60-240 °/s) were measured. More information on how velocities above and below this range affect the slope of the T-V relationship and if these effects are sex-specific is needed.

Conclusions

When PT is normalized to LBM, there are no differences in the slope of the T-V relationship between sexes for concentric muscle actions of the quadriceps and hamstrings or for eccentric muscle actions of the hamstrings. However, PT remains significantly higher in males for eccentric actions of the quadriceps at 60 and 120 °/s but not 180 or 240 °/s, resulting in a difference in the slope of the T-V relationship between sexes. MVIC of the hamstrings also remains significantly higher after normalization in males compared to females while MVIC of the quadriceps is similar between sexes. Accounting for differences between subjects, and possibly more importantly between sexes, in muscle mass by normalizing PT to LBM seems to account for many of the differences in PT between males and females along with the rate of change in PT as movement velocity increases that are often reported. More research is needed to understand why the discrepancy in PT between sexes remained for only eccentric actions of the quadriceps and MVIC of the hamstrings. Future studies should explore how normalization of PT to LBM affects the T-V relationship in other muscle groups and should seek to address the limitations of this study. Primarily, better control of physical activity level, a more thorough familiarization protocol, and to measure PT in the high-force/low-velocity and low-force/high-velocity regions of the T-V relationship is recommended.

Literature Review

The Relationship Between Muscle Force and Velocity

The relationship between muscle force and velocity was potentially first referenced by Hill in 1922 (Hill, 1922) who noted that lower rates of movement resulted in greater amounts of force being produced and vice versa. In 1935, Fenn and Marsh (Fenn & Marsh, 1935) would be the first to study the actual force-velocity (F-V) relationship (as opposed to the work-velocity relationship) which would later be outlined by Hill (1938) in his influential 1938 paper. These, along with many other studies helped lay the foundation for understanding how changes in velocity affect the force producing ability of muscle. However, it would take until 1947 that the relationship between concentric force and velocity proposed by Hill was attempted to be verified *in vivo* by Dern and colleagues (Dern et al., 1947) and it was not until 1973 that Komi published the first *in vivo* study which could be found assessing the eccentric F-V relationship (Komi, 1973).

In the nearly 90 years that the F-V relationship has been investigated, numerous studies have examined how movement velocity affects muscle force both concentrically and eccentrically, although relatively little attention has been given to the actual shape of the F-V relationship (Alcazar et al., 2019). While the decrease in muscle force as movement velocity increases has been confirmed repeatedly since Hill first outlined the F-V relationship in 1938 (Hill, 1938), the shape of the concentric F-V relationship has been proposed to be hyperbolic (Hill, 1938), double hyperbolic (Edman, 1988), and linear (Bobbert, 2012). Conversely, the lesser studied eccentric F-V relationship is not as well understood. While attempts have been made to create equations to define the eccentric F-V relationship, they only apply up to a certain amount of force (Mashima et al., 1972) or within a specific velocity range (Cole et al., 1996).

Furthermore, attempts to define the shape of the eccentric F-V relationship may be complicated by the results of *in vivo* studies measuring voluntary muscle forces conflicting with studies measuring muscle forces *in situ* or in electrically stimulated muscles. While researchers assessing eccentric forces in animal (Katz, 1939; Levin & Wyman, 1927) and human muscle preparations (Linari et al., 2004) along with *in vivo* studies on electrically stimulated muscles (Dudley et al., 1990; Pain et al., 2013; Seger & Thorstensson, 2000; Westing et al., 1990) have reported an increase in eccentric muscle forces above isometric forces, *in vivo* studies of voluntary eccentric muscle actions have shown no change (Dudley et al., 1990; Pain et al., 2013; Seger & Thorstensson, 2000; Westing et al., 1990) from isometric forces, an increase (Carney et al., 2012; Komi, 1973) in forces, and in one study (Webber & Kriellaars, 1997) a decrease in eccentric muscle force compared to isometric forces. Despite some inconsistencies, after nearly a century of research and a multitude of studies, it is generally accepted that *in vivo* eccentric muscle actions are capable of producing forces greater than is possible in isometric or concentric muscle actions (Alcazar et al., 2019; Hahn, 2018; Herzog, 2018). To what extent is still unclear. Attempts to define an equation for the eccentric F-V relationship may further be affected by a leveling off of eccentric forces that seems to happen as velocity increases, indicating that the eccentric F-V relationship may be more independent of velocity than the concentric F-V relationship even though the exact point at which this leveling off occurs has not been established (Dudley et al., 1990; Hahn et al., 2014; Holder-Powell & Rutherford, 1999).

As the shape of the F-V relationship continues to be studied, an area that warrants further investigation is potential differences in the slope (or rate of change) of the F-V relationship (or more accurately for *in-vivo* experiments, the torque velocity (T-V) relationship) between males and females. Searches for studies comparing the *in vivo* T-V relationship between sexes yielded few results with even fewer studies specifically examining the slope of the T-V relationship. In an initial review of some of these studies, de Koning et al. (1985) and Carney et al. (2012) reported no significant difference in the slope of the concentric or eccentric T-V relationship of the elbow flexors between sexes, although neither study normalized torque in any way, which may affect their findings. Comparably, in measuring peak torque (PT) and torque at a constant joint angle during concentric knee extension, Froese and Houston (1985) reported that the slope of the T-V curve was similar between males and females. However, the researchers noted that the difference in PT between sexes increased as velocity increased with less of a decline in PT in men than women, suggesting a sex specific difference. However, it is unclear what analysis was done to determine that the slope of the T-V curve was not statistically different between sexes. Additionally, results for this study are also based off absolute PT. Similarly, a study by Wagner and colleagues (Wagner et al., 1992) examining sex differences in the T-V relationship also reported a greater decrease in concentric PT in women compared to men as velocity increased for both knee extension and flexion but did not directly assess the slope of the T-V relationship. With varying results in the above studies and only one study (Carney et al., 2012) even testing the eccentric portion of the T-V relationship, it seems evident that a further review of the literature is needed. Examining research over a greater range of the T-V relationship along with research that normalizes torque to better understand how normalization affects comparisons between sexes will be helpful to assess if additional studies into potential sex-specific differences in the T-V relationship are warranted.

Assessing Muscle Torques Between Sexes

For decades, various devices have been used to control movement velocity while allowing for the measurement of the torque produced by the muscles as they rotate different parts of the body. Researchers sometimes utilize the absolute torques measured without normalizing the values between subjects based on measurements such as body mass, lean body mass, or muscle cross sectional area (CSA) to account for differences in body size. When the absolute value of measured torques across variables is utilized, the absolute values are sometimes used during analysis but may also be analyzed based on the percentage change from PT to account for absolute differences in torque between subjects. As such, the following sections are divided based on the type of normalization used (if any) and as much as possible by joint within those sections. Unless otherwise noted, statistical significance of results reported is at the $p < 0.05$ level.

Torques Based on Absolute Values and Percentage of Absolute Peak Torque

Multiple researchers have reported on comparisons of muscle torques between sexes when examining muscles that act on the knee. A study by Wagner et al. (1992) explored potential differences in the T-V relationship of male and female (n = 10 each) college students. They examined concentric knee extension and flexion from 0, 48, 96, 144, 192, 240, and 288 degrees per second (°/s) for potential differences within those velocities for PT and torque at a constant joint angle in which the lever arm was 15° below horizontal. They reported that PT decreased less (based on percent of maximal absolute PT values) in males as velocity increased than in females. A reported plateau in constant joint angle torques where torque did not change significantly between velocities also differed between sexes, with males having a plateau in torques from 0 to 192 °/s during knee extension and 0 to 96 °/s during flexion before torque significantly decreased. This plateau was measured from 0 to 144 °/s and 0 to 48 °/s for knee extension and flexion, respectively, in females. Conversely, when measuring PT of reciprocal concentric knee flexions and extensions at 60, 180, and 300 °/s in 50 males and 50 females aged

25-34, Wyatt and Edwards (1981) reported that the percentage of change between two movement velocities was similar for both sexes. However, this was based on a significance level of $p < 0.01$ instead of the more common $p < 0.05$ level.

Studying college students who were occasionally to moderately active (males n = 12, 22.4 ± 2.4 years; females n = 18, 19.8 ± 1.8 years) but were not engaged in a specific training program, Froese and Houston (1985) measured both overall PT and PT 30° before full knee extension during concentric knee extension at 45, 90, 135, 180, 225, and 270 °/s as well as maximum voluntary isometric contractions (MVIC) at a knee angle of 65°. They reported greater absolute PT at all velocities in males and greater PT after correcting torque to body mass (Nm/kg) in males than in females for all velocities except for the MVIC. However, the researchers did not find a linear relationship after normalizing torque to body weight, which they determined to mean that the correction for body weight was not statistically significant. This was the only study to report on whether normalization of torque to body mass was statistically relevant. Subsequently, reported torques and the analysis of results is based on absolute torques (Nm). Although the researchers reported the overall slope of the T-V relationship was similar between sexes, it is not clear what analysis was done to determine this. Conversely, the researchers also reported that males maintain PT better than females with females having a greater decline in PT as movement velocity increased than males. This occurred particularly when measuring torque 30° before knee extension, suggesting sex differences in the T-V relationship and that those differences may be dependent on how PT is measured. However, it is not clear how there can be a greater decline in PT in females while the slope of the T-V relationship is similar between sexes.

On the eccentric side of the T-V relationship, Cramer et al. (2002) measured isokinetic eccentric torques in the quadriceps at 30, 90, and 150 °/s in seven male (23 ± 2 years) and 8 female (23 ± 3 years) subjects. The results of this study were based on PT normalized to the highest recorded absolute value and calculated based on the percentage of that maximum value (% max). The researchers reported no significant differences in PT between sexes as movement velocity changed and no increase in PT between velocities but did report a 6% greater mean power at 90 °/s in females compared to males.

In examining concentric and eccentric actions of the knee extensors at 30, 90, and 150 °/s in male (n=15, 22.5 ± 1.7 years) and female (n=16, 22.8 ± 3.4 years) adults, Evetovich and colleagues (1998) reported a greater decline in concentric PT (non-gravity corrected) as movement velocity increased in females compared to males. However, while the magnitude of torques was greater in males, eccentric PT remained constant for both sexes as movement velocity increased. Similarly, a study by De Ste Croix et al. (2007) examining the ratio between concentric and eccentric torques during flexion and extension of the knee at 30 and 180 °/s in young (9.5±0.4 years, n = 24 males and females each), teenage (17.3±0.4 years, n = 13 males, 21 females), and adult (24.1±3.5 years, n = 12 male, 27 female) subject groups reported that females had significantly lower ratios of concentric knee flexion to eccentric knee extension for the hamstrings at both velocities than males. This lower ratio was attributed to a reduced ability to produce concentric force in females, who had lower concentric PT at both velocities than males, rather than a greater ability to generate eccentric forces, which were similar between sexes. No significant sex differences at the quadriceps were reported for the ratio of eccentric knee flexion to concentric knee extension indicating that potential sex differences may be specific to the muscles tested.

Contrasting with this, Griffin et al. (1993) reported that females (n = 50, 41.3 ± 12.0 years) demonstrated greater eccentric capacity relative to concentric than males (n = 40, 40.2 ± 12.4 years) for elbow flexors, knee flexors, and knee extensors at 30°/s and 120° /s ($p < 0.01$). Additionally, the magnitude of decrease in concentric average torque with increasing velocity for the knee extensors specifically was noted as greater for female subjects compared to males who were reported to have a similar decrease in concentric torque across all muscle groups. This also indicates that elucidating any sex-specific differences in the T-V relationship may be muscle group specific. However, the use of average torque instead of PT along with a subject age range of 21-67 years old may affect comparisons of these results with other studies.

Also studying the elbow, Otis and Godbold (1983) measured isometric PT along with concentric PT at 24, 48, 96, and 192 °/s for the elbow extensors and flexors in 15 male (30 ± 4.4 years) and nine female (26 ± 1.8 years) subjects. They reported that while males had greater absolute torques, there was no difference in the linear regression lines between sexes as velocity changed. In another study assessing concentric elbow flexion, De Koning et al.(1985) reported that despite greater absolute torques in males ($p < 0.0001$), the concavity of the T-V curve was similar between untrained males (n = 123), untrained females (n = 110), and male arm-trained athletes (n = 48) (i.e., the slope was similar between sexes), with subjects ranging in age from 15 to 36 years old. However, this study utilized a self-made apparatus that measures speed against different external loads ranging from 60 to 0 % of MVIC over every 10° of motion from 60° to 110° of elbow flexion with speed controlled only by how quickly the subject can move against that external load (De Koning et al., 1982; 1985). Subsequently, angular velocity was also reported at 10% lower in females, along with lower maximal static moment and maximal power ($p < 0.0001$ for all three), although the absolute values for these last two variables may not be the most useful for comparison between sexes (De Koning et al., 1985). Similar results were reported by Carney et al. (2012) studying eccentric torques of the elbow flexors in men (n = 20, age 24.6 ± 2.1 years) and women (n = 20, age 23.3 ± 1.8 years) at velocities of 60, 120, 180, 240, and 300 °/s. While greater absolute torques were reported in males, the changes in torque between movement velocities was similar in both sexes, resulting in the slope of the eccentric T-V relationship being similar for both males and females, however, it is not clear what analysis was done to compare slopes between sexes.

In another study, Seger and Thorstensson (1994) measured both concentric and eccentric torques of the knee extensors at 45, 90, and 180 °/s in groups (n = 10 each) of 11 year old males and females along with adult male and female physical education students ranging from 22 to 35 years old (mean 27 ± 3 years and 27 ± 4 years respectively). The researchers reported greater absolute concentric PT in the adult groups for men compared to women, however, differences between sexes in eccentric PT were not statistically significant. When normalized to body mass, there were no significant differences between sexes within age groups in PT for eccentric or concentric muscle actions. The researchers also reported that the T-V relationship displayed similar slopes for all groups, however, it is unclear what was done to compare the slope of the T-V relationship between groups. Despite this, the decrease in concentric PT as velocity increased from 45 to 180 °/s was reported as greater in both groups of females (31% for girls, 30% for women) compared to males (25% for both groups). It was not reported how concentric PT can decrease more in females compared to males while maintaining a similar slope for the T-V relationship. Additionally, no significant differences between sexes were reported in eccentric PT or in the change in PT as movement velocity increased. However, the researchers did note that after normalizing torque to body mass, eccentric torques tended to be higher (2-7%) in the group of women compared to men although this difference was not statistically significant. The researchers also reported a significant difference in the eccentric to concentric torque ratio between the adult groups with women having a greater ratio of eccentric to concentric torque than men at 180 °/s (but not 45 or 90 °/s). Furthermore, the researchers stated that they did not attempt to normalize torques to lean body mass or muscle CSA, which may have affected the results. Accordingly, it is possible that any sex differences in the magnitude of torque and rate of change in PT as movement velocity increases may only be statistically significant when comparing absolute torque values and that such differences are no longer significant when utilizing normalization methods that account for differences in muscle mass between subjects.

While the use of absolute torque in the above studies may limit the usefulness of comparison between sexes due to the lack of normalization methods that may account for physical differences between subjects and sexes, there are still some insights that can be gained from these studies. Primarily, that while the decrease in absolute concentric PT as movement velocity increases tends to be greater in females than in males (Evetovich et al., 1998; Froese & Houston, 1985; Griffin et al., 1993; Seger & Thorstensson, 1994; Wagner et al., 1992), the slope of the concentric T-V relationship is, somewhat contradictorily, still reported as being similar between sexes (De Koning et al., 1985; Froese & Houston, 1985; Otis & Godbold, 1983; Seger & Thorstensson, 1994). For eccentric torques, absolute PT does not seem to change as velocity increases in either sex (Cramer et al., 2002; Evetovich et al., 1998; Griffin et al., 1993; Seger & Thorstensson, 1994) resulting in a similar slope in the T-V relationship between sexes (Carney et al., 2012; Seger & Thorstensson, 1994). However, given that absolute values were used, potential differences in body composition that may exist between subjects and could affect comparisons between sexes are unknown. Based on these studies alone, the existence, or lack thereof, of sex-specific differences in the T-V relationship remains unclear.

Torques Normalized to Muscle Cross Sectional Area

A small number of studies were found that normalized torque to muscle CSA and compared those torques between sexes. While less common, this form of normalization may provide useful insights by allowing a more direct comparison between the amount of muscle mass and the torque generated by that muscle than is possible by more general methods of normalization.

Measuring concentric knee extensions at 180°/s in males (n = 27) and females (n = 36) aged 18 to 25, Kanehisa et al. (1996) reported greater force per unit of muscle CSA of the right thigh as assessed via ultrasound in males compared to females. A study by Bagley et al. (2021) which measured concentric knee extension torques at 60, 120, 180, and 240 °/s in 16 males and 15 females between the ages of 20 and 60 (mean 40.8 ± 3.2 years for males and 40.9 ± 3.9 years for females) also reported that men had higher torques at 180 °/s than women when torques were normalized to quadriceps muscle CSA as measured by MRI. However, sex-related differences in the sex x velocity interaction for the decrease in torque per unit of CSA at the other two movement velocities was not significantly different ($p = 0.051$) between sexes. In the only study found examining eccentric torques compared to muscle CSA between sexes, Hicks and colleagues (2016) measured eccentric torque of the knee extensors at 30 °/s in 11 male (21.1 ± 1.6 years) and 11 female (21.4 ± 1.6 years) subjects and reported no significant differences in the average PT (defined as the average of the highest PT recorded from each of six sets of 12 repetitions) between males (3.40 ± 0.78 Nm/cm^2) and females (3.15 ± 0.66 Nm/cm^2) when normalized to quadriceps CSA (as determined by ultrasound of the vastus lateralis then multiplied to estimate total quadriceps CSA).

Studying multiple joints, Schantz et al. (1983) measured concentric torques at 30, 90, and 180 °/s during both knee and elbow extension as well as elbow flexion in 11 male and 10 female physical education students and 5 male body builders (average age of 26, 27, and 28 years old, respectively). The researchers reported that maximal torque per unit of muscle CSA of the left thigh and right upper arm (determined by computed tomography scans) was not significantly different between any of the three groups for either joint at any movement velocity. Contrary to this, however, Sale et al. (1987) reported differences in PT between sexes when examining concentric elbow flexion at 30, 120, 180, 240 and 300 °/s. In their study, PT per unit of muscle CSA of the biceps brachii and brachialis (determined via computed tomography scans) decreased as velocity increased in untrained males (n = 8, 22.5 ± 1.5 years) and male body builders (n = 11, 24.8 ± 1.6 years), but not in untrained females (n = 13, 21.0 ± 0.6 years). The researchers also reported that females had a higher PT per CSA of muscle than both male groups at all velocities other than 30°/s. They speculated that the relatively greater PT at higher velocities in females compared to males may be due to differences in optimal joint angle between sexes that favors females with the greater range of motion that occurs before the resistance mechanism on an isokinetic dynamometer is engaged and PT is reached, particularly at higher movement velocities.

Measuring isometric torques only, a study by Castro et al.(1995) examined both the elbow and knee. They measured isometric elbow flexion and extension at 60° and 80° of flexion, respectively, and knee flexion and extension at 20° and 60° of flexion respectively (with 0° being full extension for both joints) in groups (n = 13 each) of untrained and trained males and females aged 18-30 years and reported no significant difference in mean upper arm or thigh torques per unit of muscle and bone CSA. However, due to the method used to obtain arm muscle CSA utilizing limb circumferences and skinfolds with a subtraction for bone, CSA for individual muscles could not be determined so results were expressed as a combination of the flexor and extensor muscles per unit CSA for both the upper arm and thigh. In addition to only measuring isometric forces, this method of obtaining muscle CSA may limit the usefulness of their results. A study by Ikai and Fukunaga (1968) also examined isometric torque during elbow flexion. They measured torque with the elbow flexed to 90° in 119 male and 126 female subjects ranging from 12 to 20 years old and reported that when compared per unit of muscle CSA of the biceps brachii and brachialis (assessed via ultrasound) that strength was almost the same between sexes.

While few studies were found that compared torque produced per unit of muscle CSA between sexes, results were greater PT in males (Bagley et al., 2021; Kanehisa et al., 1996), females (Sale et al., 1987), or no difference (Castro et al., 1995; Hicks et al., 2016; Ikai & Fukunaga, 1968; Schantz et al., 1983) between sexes for various velocities. However, with a small number of studies, few velocities measured (and two of those studies only measuring isometric torques (Castro et al., 1995; Ikai & Fukunaga, 1968)), and only one study (Hicks et al., 2016) examining eccentric forces, any conclusions that can be drawn from these studies is limited.

Torques Normalized to Body Weight

A commonly used method for normalizing results between subjects takes the torque produced and divides it by body total mass or lean body mass to provide measurements in newton meters per kilogram (Nm/kg) of body mass or lean body mass. This normalization may result in significant differences in absolute values becoming non-significant after normalization

(Claiborne et al., 2006; Neder, Nery, Silva, et al., 1999) but may provide a better comparison between sexes than can be obtained from absolute values alone. While most of the studies found which directly compare results between sexes utilized this method of normalization, comparisons of PT between sexes were generally not the primary area of focus. Additionally, few of these studies measured more than one velocity of movement, with several only measuring isometric torques. Despite these studies being unable to show sex-specific differences as movement velocity changes, reviewing these studies to see which velocities may show discrepancies between sexes could still provide useful information.

Although studies assessing isometric forces cannot provide information on how torques might vary between sexes as movement velocity increases, an understanding of how the sexes compare when no movement is involved can still be helpful when considering the entirety of the T-V relationship. Measuring MVICs of the knee flexors at 30° of flexion from full extension in 10 male (24.2 ± 2.0 years) and 10 female (21.7 ± 1.5 years) physically active subjects, Pincivero, Campy, and Coelho (2003) reported significantly greater relative torques (Nm/kg) in males (1.06 ± 0.09 Nm/kg) than in females (0.86 ± 0.21 Nm/kg). A different study by Pincivero et al.(2004) examined a range of knee joint angles, measuring isometric torques in the quadriceps at 10°, 30°, 50°, 70°, and 90° degrees of flexion in 14 male (25 ± 4 years) and 15 female (23 ± 4 years) subjects and reported greater PT in males compared to females at all joint angles remained after normalizing to body mass. A study by Maughan, Watson, and Weir (1983) measured MVICs of the quadriceps at 90° of knee flexion in 25 male (28.0 ± 5.4 years) and 25 female (25.1 ± 3.8 years) subjects, and reported that males had greater strength than females even after normalizing values to body mass (11.03 ± 1.82 N/kg and 8.42 ± 1.59 N/kg, respectively) and lean body mass (13.28 ± 1.83 N/kg and 11.53 ± 1.96 N/kg, respectively). However, when normalizing MVIC torque to muscle CSA, the greater values in males (9.49 ± 1.34 N/cm^2) were no longer significantly greater than females (8.92 ± 1.11 N/cm^2).

Examining multiple joints, Miller et al. (1993) measured MVICs for knee extension at 90° of flexion and elbow flexion at 110° of flexion in 8 male (23.3 ±1.3 years) and 8 female (25.0 ± 1.4 years) subjects. They reported that relative to lean body mass, males had both greater leg and arm strength than females with the difference more pronounced in the arms, however, precise values were not reported. As muscle CSA was also measured and showed similar results in strength between sexes per unit of muscle CSA the greater strength relative to lean body mass in males was attributed to larger muscle fibers. Similar results were reported by Stearns, Keim, and Powers (2013) in a study on hip and knee extensors. They measured MVICs of the hip at 60° and knee at 90° of flexion, respectively, in 20 male (23.2 ± 1.3 years) and 20 female (23.7 ± 1.2 years) subjects and reported greater torques normalized to body mass ($p < 0.001$) in males than in females both at the knee (3.66 ± 0.6 Nm/kg and 2.82 ± 0.4 Nm/kg, respectively) and hip (4.27 ± 1.0 Nm/kg and 2.87 ± 0.8 Nm/kg, respectively). Also assessing multiple joints, Avin et al. (2010) measured MVICs for elbow flexion at 60° of flexion and ankle dorsiflexion with the ankle positioned at 20° of plantarflexion in 16 male (24.4 ± 1.4 years) and 16 female (23.0 ± 0.5 years) subjects. They reported greater normalized PT in males compared to females for both the ankle (0.58 ± 0.02 Nm/kg to 0.51 ± 0.01 Nm/kg) and elbow (0.97 ± 0.03 Nm/kg to 0.58 ± 0.03 Nm/kg). In another study examining the hip, Shih et al. (2021) measured hip extension MVICs in 15 male (28.5 ± 5.3 years) and 17 female (26.7 ± 3.4) subjects with the hip at 60° of flexion and the knee flexed to 90° and reported greater PT ($p < 0.01$) in male (6.15 ± 1.72 Nm/kg) subjects compared to females (4.42 ± 1.11 Nm/kg/m^2) when normalizing torque to body mass index (body mass in kg divided by body height in meters squared). In another isometric study of the hip, Jacobs et al. (2007) measured MVIC of hip abductors with subjects lying on their side and the hip in a neutral position. With 15 male (24.4 ± 3.0 years) and 15 female (23.2 ± 2.9 years) subjects, they normalized PT by body weight and height (%BWh) and reported greater PT in males (7.2 ± 1.5% BWh) compared to females (5.8 ± 1.2% BWh). Somewhat uniquely, Komi and Karlsson (1978) studied homozygous and dizygous twins between the ages of 15-24 years old (with the exception of one pair). They measured MVICs during knee extension at an unspecified joint angle and was the only study measuring isometric torques to report no significant difference between sexes (males = 3.40 kp/kg, females = 3.38 kp/kg) when torque was normalized to body weight.

Several other studies, mostly examining the knee, utilized a single movement velocity in their comparisons between sexes. Of the different velocities studied, 60 °/s was the most common. Measuring concentric knee extensor torque at 60°/s between males (n = 15, 21.7 ± 3.6 years) and females (n = 15, 21.5 ± 3.9 years), Pincivero, Dixon, et al. (2003) reported significantly greater torque in males (2.74 ± 0.34 Nm/kg) than in females (2.26 ± 0.34 Nm/kg) when corrected for body mass. In a study that examined Division I athletes (n = 60 males, 40 females, average age 19.7 years) and a non-athletic control group of males and females (n = 26 males, 14 females, average age 23.5 years), Huston and Wojtys (1996) also reported greater torques normalized to body weight (foot-pounds torque/body weight in pounds) in both male groups compared to the female groups for concentric knee extension and flexion at 60 °/s. Comparing Division I female college athletes (n = 15, 19.3 ± 1.2 years) to male (n = 15, 21.26 ± 1.55 years) recreational athletes, Lephart et al. (2002) reported greater PT to body mass during both concentric knee extension and flexion at 60°/s in males than females even when subjects were matched based on age and activity level. However, the body mass adjusted torques are not provided in the study. A similar result was reported by Burfeind, Hong, and Stavrianeas (2012) in their study on NCAA division 3 soccer players. They reported greater PT normalized to body weight in males (n = 29, 18.9 ± 1.1 years) than in females (n = 23, 19.2 ± 1.2 years) during concentric knee extension (1.44 ± 0.23 Nm/kg and 0.99 ± 0.38 Nm/kg respectively) and flexion (0.80 ± 0.15 Nm/kg and 0.62 ± 0.08 respectively) at 60°/s.

Examining multiple joints, and one of a few studies to measure eccentric torque, De Marche Baldon and colleagues (2011) measured eccentric PT at the knee and hip in recreational college athletes. They reported greater body mass corrected PT ($p < 0.001$) in males (n = 17, 21.8 ± 2.7 years) compared to females (n = 22, 20.3 ± 1.6 years) during eccentric knee flexion (2.08 ± 0.29 Nm/kg and 1.43 ± 0.20 Nm/kg, respectively) and extension (4.45 ± 0.45 Nm/kg and 3.56 ± 0.50 Nm/kg, respectively) at 60 °/s. Lower eccentric PT in females relative to males were also reported when measuring hip abduction (1.32 ± 0.18 Nm/kg and 1.85 ± 0.24 Nm/kg, respectively) and adduction (2.05 ± 0.24 Nm/kg and 2.60 ± 0.40 Nm/kg, respectively) along with medial (1.50 ± 0.37 Nm/kg and 1.85 ± 0.24 Nm/kg, respectively) and lateral hip rotation (0.79 ± 0.16 Nm/kg and 1.33 ± 0.16 Nm/kg, respectively).

Also measuring torques at the knee and hip, Claiborne et al. (2006) examined concentric and eccentric torques in 15 males (26.4 ± 5.2 years) and 15 females (23.5 ± 3.7 years) at 60 °/s. Males were reported to generate greater absolute PT for concentric and eccentric movements in knee extension and flexion, hip external rotation, hip extension and flexion, hip abduction and adduction, hip external rotation, and hip concentric internal rotation, but not eccentric internal rotation. However, after normalizing PT to body mass, significantly greater differences were only reported for males compared to females for concentric knee flexion (1.43 Nm/kg to 1.24 Nm/kg (standard deviations not provided)) and extension (1.77 Nm/kg to 1.47 Nm/kg), concentric hip adduction (1.5 Nm/kg to 1.31 Nm/kg), and concentric hip flexion (1.75 Nm/kg to 1.41 Nm/kg), as well as greater eccentric hip extension (1.67 Nm/kg to 1.48 Nm/kg), suggesting that differences between sexes may be greater with concentric actions rather than eccentric, at least for some joint movements. In another study assessing hip torques, Sugimoto et al. (2014) reported greater PT normalized to body mass in males (n = 16, 20.5 ± 1.6 years) than females (n = 17, 26.7 ± 3.4 years) during hip abduction (1.29 ± 0.24 Nm/kg to 1.13 ± 0.20 Nm/kg, respectively) but not adduction (both at 60 °/s), where PT was similar between sexes (males 0.75 ± 0.32 Nm/kg, females 0.72 ± 0.27 Nm/kg).

Other researchers also reported that normalizing torque to body weight abolishes at least some, if not all, torque differences between sexes when measuring movements at 60 °/s. Studying older male (n = 20, 75.4 ± 5.5 years) and female (n = 20, 73.6 ± 5.0 years) subjects, Musselman and Brouwer (2005) measured reciprocal concentric extension and flexion in the knee, hip, and ankle at 60°/s. They reported higher concentric PT normalized to body weight in males than in females at the hip and knee for both extension and flexion, and at the ankle for dorsiflexion but not plantarflexion, however, specific torque values were not provided. Heyward, Johannes-Ellis, and Romer (1986) measured concentric torque at 60 °/s during shoulder flexion and knee extension in 48 male (24.67 ± 5.94 years) and 55 female (24.82 ± 4.74 years) subjects and reported no significant differences in PT after normalizing results to lean body mass. Again, however, adjusted PT values were not reported in the study.

Somewhat interestingly, a study by Neder, Nery, Silva et al. (1999) measuring PT during concentric knee extensions at 60 °/s in three separate age groups (20-39 years, males n = 9, females n = 11; 40-59 years, males n = 11, females n = 13; 60-80 years, males n = 14, females n = 17) reported greater PT for males compared to age grouped females for all three age groups when comparing absolute and allometrically corrected PT, but not when PT was normalized to bone-free lean leg mass (values not reported). However, normalizing the torque to only leg muscle mass as opposed to whole body mass or lean mass makes comparing this result to other studies more challenging. Another study by Neder and colleagues (Neder, Nery, Shinzato, et al., 1999) also comparing PT over a large age range of subjects but not divided into separate groups this time, measured concentric PT of the knee extensors and flexors again at 60 °/s in 45 male and 51 female (aged 20-80, average 49.8 ± 18.1 for males and 51.7 ± 17.7 for females) subjects. The researchers again reported that when correcting PT to bone-free lean leg mass there were no longer significant differences in PT between sexes (values not reported).

While studies measuring PT at 60 °/s are more common when only assessing one velocity, other researchers examined different movement velocities. Measuring concentric and eccentric knee extension and flexion at 50 °/s in younger (15-24 years, males n = 33, females n = 49) and older (25-34 years, males n = 21, females n = 24) groups, Highgenboten, Jackson, and Meske (1988) reported significantly greater weight-adjusted PT ($p < 0.01$) in males compared to females for concentric actions of the knee extensors (2.76 ± 0.66 Nm/kg to 2.12 ± 0.51 Nm/kg) and flexors (1.16 ± 0.26 Nm/kg to 0.85 ± 0.17 Nm/kg) and eccentric actions of the knee extensors (2.88 ± 0.86 Nm/kg to 2.36 ± 0.85 Nm/kg) and flexors (1.40 ± 0.33 Nm/kg to 1.06 ± 0.26 Nm/kg). Wretling and Henriksson-Larsen (1998) also reported significantly greater PT when corrected to body mass in concentric knee extension at 90 °/s in males compared to females (n = 8 each) between the ages of 20 and 38 (mean 26 years), although the specific body mass adjusted values were not reported. Stock et al. (2013) also measured concentric knee extension but at 180 °/s and in college aged males (n = 20, 22 ± 2 years) and females (n = 20, 22 ± 1 years). They reported significantly greater PT ($p < 0.001$) in males (2.00 ± 0.29 Nm/kg) than in females (1.51 ± 0.25 Nm/kg). Similarly, Pincivero et al. (2000) also measured concentric PT of the quadriceps during knee extension at 180 °/s in males (n = 16, 23.4 ± 3.7 years) and females (n = 16, 21.2 ± 1.8 years). They reported greater PT after adjusting for body weight in males (1.35 ± 0.17 Nm/kg) than females (1.10 ± 0.11 Nm/kg). In another study, Pincivero, Gandaio, and Ito (2003), measured concentric PT of the knee at 180 °/s of movement. Examining 19 male (24.6 ± 3.8 years) and 20 female (24 ± 4.2 years) subjects. They also reported greater PT normalized to body mass in males compared to females for knee extension (2.11 ± 0.22 Nm/kg to 1.53 ± 0.21 Nm/kg) and flexion (1.23 ± 0.15 Nm/kg to 0.93 ± 0.14 Nm/kg). Also examining the knee, Fujisawa et al.(2017) measured concentric knee extensor torque at 180 °/s in 10 males (21.4 ± 0.49 years) and nine women (20.8 ± 1.33 years) and reported greater torque normalized to body weight in males (1.99 ± 0.19 Nm/kg) than females (1.43 ± 0.22 Nm/kg). Borda et al. (2014), however, reported no significant differences in PT relative to body mass between 10 male (29.6 ± 4.5 years) and 12 female (27.0 ± 6.9) subjects during concentric knee extension (males 1.10 ± 0.28 Nm/kg, females 1.10 ± 0.17 Nm/kg) and flexion (males 0.61 ± 0.14 Nm/kg, females 0.59 ± 0.16 Nm/kg) at a movement velocity of 180 °/s.

Exploring torques at the hip, Brent et al. (2013) measured concentric hip abduction at 120 °/s in adolescent soccer and basketball players in age matched groups from 11 to 18 years old (males n = 79, 13.65 ±1.6 years; females n = 272, 14.0 ± 2.2 years). They reported significantly greater torque relative to body mass in males than females for both the dominant and non-dominant legs. In another study on the hip and one of the few studies examining eccentric torques, Jacobs and Mattacola (2005) measured eccentric hip abductor torque at 120 °/s in recreationally active adults (n = 8 males, 24.1 ± 2.2 years; n = 10 females, 22.1 ± 2.3 years) and reported no significant differences in average PT between sexes (males 1.41 ± 0.25 Nm/kg, females 1.45 ± 0.35 Nm/kg).

Although the above studies compared muscle torques between sexes, the use of only a single velocity in any one study severely limits the usefulness of those comparisons in trying to determine a sex difference in the T-V relationship. While these studies mostly reported a greater PT in males relative to females at the measured velocity, the small number of studies at most movement velocities for a specific joint and muscle action makes it difficult to draw useful conclusions about any potential sex-specific differences regarding the rate of change within the T-V relationship.

A small number of studies were also found that utilized multiple movement velocities that may be helpful in elucidating possible differences between sexes in PT as movement velocity changes. Measuring torques during concentric knee extension and flexion at 90 and 180 °/s as well as a MVIC at 90° of knee flexion, Lisee et al. (2019) studied 75 male and 45 female subjects (combined 21.44 ± 2.92 years). When comparing PT between sexes, they reported greater torques in males than females for MVIC as well as both movement velocities during both flexion and extension after normalizing torque to body mass but did not report on any differences in the rate of change in torques between movement velocities. In more closely examining the reported torques and the change in torque between movement velocities, isokinetic PT for knee extension decreased from 2.60 ± 0.42 Nm/kg at 90 °/s to 2.05 ± 0.33 Nm/kg at 180 °/s for males and 2.04 ± 0.26 Nm/kg to 1.60 ± 0.22 Nm/kg in females. For knee flexion, the change in PT between velocities went from 1.21 ± 0.26 Nm/kg to 0.94 ± 0.24 Nm/kg in males and 0.98 ± 0.16 Nm/kg to 0.76 ± 0.13 Nm/kg in females. This resulted in a 0.55 Nm/kg decrease between velocities for males, and 0.44 Nm/kg for females during knee extension and 0.27 Nm/kg and

0.22 Nm/kg decrease during knee flexion for males and females, respectively. As the researchers did not report on any potential sex differences for changes in PT as movement velocity increased it is not possible to determine if this difference is statistically significant, however, it does indicate the possibility of a smaller decrease in PT as movement velocity increases in females relative to males.

In a study by Anderson et al. (2001) the researchers measured PT during concentric knee extension and flexion at 60 and 240 °/s in 50 male (16.1 years) and 50 female (16.2 years) high school varsity basketball players. After adjusting PT to body mass, the male players were reported to generate greater PT than female players for knee extension and flexion at both movement velocities. While the specific unit of measurement or method of adjusting PT to body mass was not reported, the adjusted values given for PT at 60 °/s of knee extension was 51.3 (standard deviation not reported) for males and 43.8 for females, with torque decreasing at 240 °/s of movement to 32.1 in males and 28.5 in females, giving a decrease of 19.2 for males and 15.3 for females as movement velocity increased. For knee flexion, the PT decreased in male subjects from 68.6 to 48.4 between velocities and 60.2 to 41.5 for female subjects resulting in a 20.2 and 18.7 unit decrease for males and females, respectively. While more information on the method of normalizing PT to body mass along with specific units for PT would be beneficial, the information provided again indicates a smaller decrease in PT as movement velocity increased for females relative to males. However, statistical significance between those decreases cannot be determined.

Colliander and Tesch (1989) examined 27 male (27 ± 5 years) and 13 female (27 ± 4 years) physically active subjects with no history of strength training or participation in competitive sports that emphasized strength or power. In the study, they measured concentric and eccentric torque during bilateral (i.e. both legs measured together) knee extension and flexion at 30, 90, and 150 °/s of movement. They reported that PT relative to body mass was greater in males than females during concentric knee extension and flexion while eccentric torques were similar between sexes. However, the researchers noted different patterns for females compared to males for the eccentric T-V relationship. In males, eccentric quadriceps peak torque decreased with an increase in movement velocity (7.17 ± 1.62 Nm/kg, 6.90 ± 1.37 Nm/kg, and 6.67 ± 1.63 Nm/kg at 30, 90, and 150 °/s respectively) while hamstring torque showed no significant change (3.59 ± 0.71 Nm/kg, 3.70 ± 0.79 Nm/kg, and 3.71 ± 0.76 Nm/kg), but in females eccentric quadriceps and hamstring torque increased as movement velocity increased (quadriceps - 6.47 ± 1.42 Nm/kg, 7.02 ± 1.32 Nm/kg, and 6.58 ± 1.04 Nm/kg; hamstrings - 3.00 ± 0.54 Nm/kg, 3.32 ± 0.43 Nm/kg, and 3.41 ± 0.44 Nm/kg). The difference in eccentric torques also resulted in a greater difference between quadriceps eccentric torque relative to concentric torque in females compared to males at movement velocities of 90 and 150 °/s but not 30 °/s. This suggests a difference between sexes regarding the response to eccentric versus concentric muscle actions though to what degree and if this potential difference would affect the slope of the T-V relationship is unclear. Additionally, the bilateral nature of the study may affect the ability to compare these results to other studies measuring torques unilaterally.

In another study, Colliander and Tesch (1991) measured concentric and eccentric actions of the quadriceps at 30, 90, and 150 °/s to assess the effects of a 12-week resistance training program in 11 male (26 ± 5 years) and 11 female (27 ±4 years) physically active subjects that had never engaged in a regular strength training program before. They reported that concentric PT relative to body mass was greater in males than in females at all velocities both before and after the training program while eccentric PT relative to body mass did not differ between sexes.

When comparing the change in PT as movement velocity increased, the researchers noted a greater decrease in concentric PT in females relative to males before the training program but not after. However, while within group comparisons reported no change in eccentric PT as movement velocity increased, when comparing between sexes the researchers reported a greater decrease in eccentric PT in males compared to females after the training program but not before. Both these changes were attributed to greater changes at the lowest velocity measured (30 °/s) for males relative to females, with the T-V relationship changing in males but not females after the training program. These results indicate that there are sex-specific differences in the T-V relationship and that those differences may vary based on the resistance training status of the subjects.

Other researchers reported no significant differences between sexes in the rate of change of muscle torque as movement velocity increases. A study by Kong and Burns (2010) measured concentric torque during knee extension and flexion at 60, 180, and 300 °/s as well as isometric torque at every 10° of knee flexion from 40 to 90° in 25 male (25.5 ± 6.0 years) and 15 female (24.2 ± 7.4 years) recreationally active subjects. While the researchers reported that isometric torque of the quadriceps was greater overall in males (1.9 - 3.2 Nm/kg) than females (1.6 – 2.7 Nm/kg), isometric torque for the hamstrings and isokinetic torques (values not reported) at all three movement velocities for both muscle groups did not have any significant differences between sexes.

With only a few studies measuring PT across velocities and comparing the results between sexes it is difficult to draw meaningful conclusions from this limited number of studies. While not specifically assessed in all studies, when concentric PT is normalized to body mass it is possible that torque decreases more slowly as velocity increases in females relative to males

(Anderson et al., 2001; Lisee et al., 2019) although other researchers would report no significant differences in the rate of change in concentric PT between sexes (Colliander & Tesch, 1989, 1991; Kong & Burns, 2010). For the eccentric T-V relationship, there may be a decrease in eccentric PT as velocity increases in males relative to females (Colliander & Tesch, 1989, 1991). However, differences within both the concentric and eccentric T-V relationship may depend on the training status of the subjects, particularly males (Colliander & Tesch, 1991). Overall, too few studies have measured the T-V relationship between sexes with torque normalized to body mass for any definitive conclusions to be drawn.

Summary of Literature Review

Overall, most researchers reported greater PT in males compared to females even when torque is normalized by muscle CSA (Bagley et al., 2021; Kanehisa et al., 1996) or body mass (Anderson et al., 2001; Avin et al., 2010; Brent et al., 2013; Burfeind et al., 2012; Claiborne et al., 2006; Colliander & Tesch, 1991; Fujisawa et al., 2017; Highgenboten et al., 1988; Huston & Wojtys, 1996; Jacobs et al., 2007; Lephart et al., 2002; Lisee et al., 2019; Maughan et al., 1983; Miller et al., 1993; Musselman & Brouwer, 2005; Pincivero, Gandaio, et al., 2003; Pincivero, Campy, et al., 2003; Pincivero, Dixon, et al., 2003; Pincivero et al., 2004; Shih et al., 2021; Stearns et al., 2013; Stock et al., 2013; Sugimoto et al., 2014; Wretling & Henriksson-Larsén, 1998), although some reported no significant differences in PT between sexes after normalizing the results (Borda et al., 2014; Castro et al., 1995; Claiborne et al., 2006; Heyward et al., 1986; Hicks et al., 2016; Ikai & Fukunaga, 1968; Jacobs & Mattacola, 2005; Komi & Karlsson, 1978; Kong & Burns, 2010; Neder, Nery, Silva, et al., 1999; Neder, Nery, Shinzato, et al., 1999; Schantz et al., 1983; Sugimoto et al., 2014). When examining the ratio of concentric to eccentric torque, the reported results again conflict. In one study, the researchers reported lower concentric relative to eccentric PT in females compared to males (Mark De Ste Croix et al., 2007) while others reported this ratio was greater in females relative to males (Colliander & Tesch, 1989; Griffin et al., 1993; Seger & Thorstensson, 1994). The reasoning for this difference is also attributed to both a lower ability to produce concentric torque in females rather than greater eccentric torque (Mark De Ste Croix et al., 2007) and the opposite of a greater ability to produce eccentric torque in females compared to males (Griffin et al., 1993).

The rate of change in PT as movement velocity increases is also not clear. Some researchers reported a greater decrease in concentric PT in females compared to males as movement velocity increases (Evetovich et al., 1998; Froese & Houston, 1985; Griffin et al., 1993; Seger & Thorstensson, 1994; Wagner et al., 1992), although this difference may only be measured when comparing absolute torques and may not exist after normalizing torques to body mass (Colliander & Tesch, 1989, 1991; Kong & Burns, 2010). While the results of studies by Lisee et al.(2019) and Anderson et al. (2001) indicate that body mass normalized PT may decline less as movement velocity increases in females, the rate of change in PT was not analyzed so this difference may not be statistically significant and leaves fewer studies to compare results between for how normalizing PT affects potential differences in the T-V relationship between sexes. Compared to concentric muscle actions, eccentric torque seems to have less variability in the reported results with PT generally not changing significantly in either males or females as movement velocity increases (Carney et al., 2012; Cramer et al., 2002; Evetovich et al., 1998; Griffin et al., 1993; Seger & Thorstensson, 1994) although increases in eccentric PT in females (Colliander & Tesch, 1989) along with decreases in PT in males (Colliander & Tesch, 1989, 1991) as movement velocity increases have also been reported.

Despite these reported differences in the rate of change in concentric torques as movement velocity increases (Evetovich et al., 1998; Froese & Houston, 1985; Griffin et al., 1993; Seger & Thorstensson, 1994; Wagner et al., 1992), in studies where the slope of the T-V relationship was compared between sexes the researchers consistently reported no differences between sexes in the slope of the T-V relationship (Carney et al., 2012; De Koning et al., 1982; Froese & Houston, 1985; Otis & Godbold, 1983; Seger & Thorstensson, 1994). However, the method used to compare slopes was not reported in most studies (Carney et al., 2012; Froese & Houston, 1985; Seger & Thorstensson, 1994) with only one (De Koning et al., 1982) that reported using Hill's equation (Hill, 1938) and another compared linear regression lines (Otis & Godbold, 1983). Of the studies that examined the eccentric T-V relationship, it was not reported how the slope of the T-V relationship was compared between sexes in either of these studies (Carney et al., 2012; Seger & Thorstensson, 1994). Additionally, all the studies that compared the slope of the T-V relationship between sexes utilized absolute torques which cannot account for differences in body mass, particularly lean body mass, between subjects that may affect the results. As such, further research comparing the slope of the T-V relationship between sexes utilizing normalization methods that allow for better comparisons of PT between subjects of different sizes and differing amounts of muscle mass should be conducted to better elucidate any potential sex-specific differences in the T-V relationship.

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Appendix A: Journal of Human Movement Science Author Guidelines

Submission guidelines for the journal of Human Movement Science.

Appendix B: Individual Data

Table B.1

Subject Characteristics

Subject #	Age (yrs)	Dry Weight (kg)	Height (m)	Lean Body Mass (kg)	Fat Mass (kg)	% Body Fat
M1	21	79.72	1.84	67.20	12.52	15.70
M2	21	73.26	1.88	62.04	11.22	15.31
M3	26	76.66	1.83	65.74	10.92	14.25
M4	22	69.74	1.76	59.82	9.92	14.23
M5	22	71.21	1.75	60.10	11.12	15.61
M6	21	75.07	1.87	64.93	10.14	13.50
M7	21	70.65	1.80	56.41	14.23	20.15
M8	19	76.54	1.91	64.70	11.84	15.47
M9	20	78.36	1.79	70.23	8.13	10.37
M10	19	74.28	1.85	63.72	10.55	14.21
M11	20	67.81	1.71	54.41	13.41	19.77
M12	20	73.14	1.66	64.19	8.95	12.24
M13	21	98.88	1.80	84.63	14.25	14.41
M14	21	73.60	1.76	65.23	8.37	11.37
M15	24	93.67	1.72	65.04	28.63	30.56
M16	20	79.83	1.84	71.65	8.18	10.24
F1	19	72.35	1.75	52.64	19.71	27.24
F2	22	62.48	1.78	48.02	14.47	23.15
F3	21	52.73	1.58	41.31	11.42	21.66
F4	22	63.28	1.70	49.27	14.01	22.14
F5	21	60.33	1.61	48.25	12.08	20.02
F6	20	75.41	1.77	56.56	18.85	25.00
F7	22	80.97	1.70	59.20	21.77	26.88
F8	24	53.98	1.54	44.28	9.69	17.96
F9	21	51.48	1.61	40.06	11.42	22.19
F10	19	98.32	1.69	58.10	40.22	40.91

Note: For subject #, M = males, F = females

Table B.2

Male Quadriceps Absolute Peak Torque

Subject #	CON 60 (Nm)	CON 120 (Nm)	CON 180 (Nm)	CON 240 (Nm)	ISO (Nm)
1	259.8	212.3	164.1	151.2	249.2
2	219.9	201.7	164.3	170.0	270.5
3	232.5	186.6	157.8	144.3	250.1
4	197.0	171.0	151.6	133.3	291.0
5	278.1	212.3	167.4	149.0	238.8
6	244.7	203.6	159.7	132.2	241.9
7	202.7	172.3	163.9	138.0	301.1
8	217.5	218.4	183.7	168.1	274.3
9	238.5	240.4	148.6	176.1	259.6
10	235.6	187.8	152.5	142.6	239.2
11	180.5	130.8	131.4	104.7	203.6
12	215.2	204.3	172.6	165.4	242.3
13	293.5	245.9	221.0	197.0	374.5
14	162.3	190.0	158.9	137.3	239.8
15	266.0	212.3	182.1	165.8	255.2
16	224.8	179.1	170.7	159.6	220.0
Subject #	ECC 60 (Nm)	ECC 120 (Nm)	ECC 180 (Nm)	ECC 240 (Nm)	
1	322.1	283.6	281.7	303.2	
2	334.1	314.5	296.7	256.0	
3	271.4	286.3	210.0	205.7	
4	251.5	286.6	259.2	294.8	
5	317.9	291.8	294.5	323.2	
6	253.8	266.6	280.1	221.8	
7	244.0	247.8	250.7	237.8	
8	289.1	272.9	303.7	297.7	
9	281.9	243.5	243.5	246.5	
10	268.3	277.5	271.7	274.0	
11	191.3	178.6	171.1	174.6	
12	327.4	310.9	287.3	267.9	
13	441.6	379.5	363.5	383.0	
14	167.6	222.8	167.2	179.0	
15	246.8	250.4	186.2	199.6	
16	250.8	183.6	202.6	201.5	

Note: CON = concentric, ISO = isometric, ECC = eccentric; 60, 120, 180, and 240 correspond with the °/s of movement velocity

Table B.3

Female Quadriceps Absolute Peak Torque

Subject #	CON 60 (Nm)	CON 120 (Nm)	CON 180 (Nm)	CON 240 (Nm)	ISO (Nm)
1	199.6	167.3	131.9	129.1	253.4
2	180.6	137.8	125.1	96.3	202.2
3	86.2	73.2	50.7	60.6	88.4
4	185.2	162.3	137.9	123.1	213.3
5	165.8	136.4	125.7	113.6	202.4
6	184.4	138.3	115.5	104.9	240.4
7	150.2	126.1	105.1	64.5	143.0
8	83.4	81.6	68.3	63.5	129.8
9	131.0	120.1	107.4	98.3	110.6
10	190.2	176.4	143.6	132.1	224.5
Subject #	ECC 60 (Nm)	ECC 120 (Nm)	ECC 180 (Nm)	ECC 240 (Nm)	
1	215.7	183.4	189.4	211.8	
2	243.4	239.2	250.3	244.6	
3	93.4	99.1	111.3	107.4	
4	226.0	235.6	238.2	249.9	
5	194.2	221.0	233.5	225.5	
6	183.4	162.7	193.2	150.6	
7	142.0	120.5	118.0	126.9	
8	126.9	111.9	125.5	137.8	
9	108.1	101.6	130.7	126.0	
10	153.1	155.1	163.0	125.5	

Note: CON = concentric, ISO = isometric, ECC = eccentric; 60, 120, 180, and 240 correspond with the °/s of movement velocity

Table B.4

Male Hamstrings Absolute Peak Torque

Subject #	CON 60 (Nm)	CON 120 (Nm)	CON 180 (Nm)	CON 240 (Nm)	ISO (Nm)
1	132.5	124.1	118.1	98.7	140.2
2	81.5	88.8	64.0	68.5	132.1
3	111.3	99.5	88.0	75.4	117.7
4	106.4	99.4	87.2	77.3	134.1
5	173.5	132.6	129.6	95.2	164.6
6	127.2	110.9	88.9	68.7	166.2
7	119.6	114.3	106.4	96.7	146.8
8	113.2	116.3	98.3	83.5	152.7
9	144.0	140.5	97.1	102.6	141.4
10	125.5	95.4	101.7	72.8	145.2
11	91.8	77.3	84.7	66.4	99.4
12	115.9	113.5	106.6	102.8	118.5
13	143.2	129.1	107.5	107.1	161.9
14	84.7	103.2	96.5	94.8	122.6
15	119.4	101.8	89.1	82.2	126.4
16	126.8	111.7	105.9	90.4	171.0
Subject #	ECC 60 (Nm)	ECC 120 (Nm)	ECC 180 (Nm)	ECC 240 (Nm)	
1	216.0	209.6	210.4	211.5	
2	229.3	221.8	224.5	234.7	
3	246.2	232.7	217.7	215.0	
4	188.3	236.5	193.9	213.0	
5	247.7	260.0	222.6	229.3	
6	218.7	227.2	248.5	208.3	
7	214.8	201.1	200.9	205.0	
8	196.6	197.8	216.7	208.8	
9	210.0	172.9	190.8	194.0	
10	225.5	235.1	243.9	243.4	
11	146.3	142.9	161.7	147.0	
12	255.7	194.6	194.8	181.3	
13	270.6	243.0	235.4	251.5	
14	143.4	173.1	149.1	149.4	
15	224.8	250.4	230.1	214.1	
16	240.9	211.5	214.6	228.2	

Note: CON = concentric, ISO = isometric, ECC = eccentric; 60, 120, 180, and 240 correspond with the °/s of movement velocity

Table B.5

Female Hamstrings Absolute Peak Torque

Subject #	CON 60 (Nm)	CON 120 (Nm)	CON 180 (Nm)	CON 240 (Nm)	ISO (Nm)
1	81.6	65.5	59.9	55.6	97.5
2	88.4	72.7	59.4	52.9	106.2
3	51.2	49.2	43.1	45.8	53.6
4	94.0	88.0	75.0	68.1	111.2
5	75.4	70.2	67.1	57.1	93.4
6	73.1	64.5	59.0	51.1	104.4
7	59.1	54.4	38.6	25.2	63.3
8	59.8	56.1	39.3	40.1	82.6
9	55.9	57.5	57.5	54.1	68.9
10	90.3	70.9	59.4	50.0	120.9
Subject #	ECC 60 (Nm)	ECC 120 (Nm)	ECC 180 (Nm)	ECC 240 (Nm)	
1	159.3	162.4	159.0	176.7	
2	140.1	138.8	134.9	136.4	
3	93.6	82.2	92.1	87.7	
4	173.8	170.3	171.0	175.7	
5	139.9	147.4	135.4	143.2	
6	126.4	133.3	143.0	138.6	
7	140.1	119.4	120.4	131.6	
8	130.0	100.2	113.5	126.2	
9	125.3	107.1	124.6	121.2	
10	169.7	156.5	168.1	113.5	

Note: CON = concentric, ISO = isometric, ECC = eccentric; 60, 120, 180, and 240 correspond with the °/s of movement velocity

Table B.6

Male Quadriceps Adjusted Peak Torque

Subject #	CON 60 (Nm/kg)	CON 120 (Nm/kg)	CON 180 (Nm/kg)	CON 240 (Nm/kg)	ISO (Nm/kg)
1	3.9	3.2	2.4	2.2	3.7
2	3.5	3.3	2.6	2.7	4.4
3	3.5	2.8	2.4	2.2	3.8
4	3.3	2.9	2.5	2.2	4.9
5	4.6	3.5	2.8	2.5	4.0
6	3.8	3.1	2.5	2.0	3.7
7	3.6	3.1	2.9	2.4	5.3
8	3.4	3.4	2.8	2.6	4.2
9	3.4	3.4	2.1	2.5	3.7
10	3.7	2.9	2.4	2.2	3.8
11	3.3	2.4	2.4	1.9	3.7
12	3.4	3.2	2.7	2.6	3.8
13	3.5	2.9	2.6	2.3	4.4
14	2.5	2.9	2.4	2.1	3.7
15	4.1	3.3	2.8	2.5	3.9
16	3.1	2.5	2.4	2.2	3.1
Subject #	ECC 60 (Nm/kg)	ECC 120 (Nm/kg)	ECC 180 (Nm/kg)	ECC 240 (Nm/kg)	
1	4.8	4.2	4.2	4.5	
2	5.4	5.1	4.8	4.1	
3	4.1	4.4	3.2	3.1	
4	4.2	4.8	4.3	4.9	
5	5.3	4.9	4.9	5.4	
6	3.9	4.1	4.3	3.4	
7	4.3	4.4	4.4	4.2	
8	4.5	4.2	4.7	4.6	
9	4.0	3.5	3.5	3.5	
10	4.2	4.4	4.3	4.3	
11	3.5	3.3	3.1	3.2	
12	5.1	4.8	4.5	4.2	
13	5.2	4.5	4.3	4.5	
14	2.6	3.4	2.6	2.7	
15	3.8	3.8	2.9	3.1	
16	3.5	2.6	2.8	2.8	

Note: CON = concentric, ISO = isometric, ECC = eccentric; 60, 120, 180, and 240 correspond with the °/s of movement velocity

Table B.7

Female Quadriceps Adjusted Peak Torque

Subject #	CON 60 (Nm/kg)	CON 120 (Nm/kg)	CON 180 (Nm/kg)	CON 240 (Nm/kg)	ISO (Nm/kg)
1	3.8	3.2	2.5	2.5	4.8
2	3.8	2.9	2.6	2.0	4.2
3	2.1	1.8	1.2	1.5	2.1
4	3.8	3.3	2.8	2.5	4.3
5	3.4	2.8	2.6	2.4	4.2
6	3.3	2.4	2.0	1.9	4.3
7	2.5	2.1	1.8	1.1	2.4
8	1.9	1.8	1.5	1.4	2.9
9	3.3	3.0	2.7	2.5	2.8
10	3.3	3.0	2.5	2.3	3.9
Subject #	ECC 60 (Nm/kg)	ECC 120 (Nm/kg)	ECC 180 (Nm/kg)	ECC 240 (Nm/kg)	
1	4.1	3.5	3.6	4.0	
2	5.1	5.0	5.2	5.1	
3	2.3	2.4	2.7	2.6	
4	4.6	4.8	4.8	5.1	
5	4.0	4.6	4.8	4.7	
6	3.2	2.9	3.4	2.7	
7	2.4	2.0	2.0	2.1	
8	2.9	2.5	2.8	3.1	
9	2.7	2.5	3.3	3.1	
10	2.6	2.7	2.8	2.2	

Note: CON = concentric, ISO = isometric, ECC = eccentric; 60, 120, 180, and 240 correspond with the °/s of movement velocity

Table B.8

Male Hamstrings Adjusted Peak Torque

Subject #	CON 60 (Nm/kg)	CON 120 (Nm/kg)	CON 180 (Nm/kg)	CON 240 (Nm/kg)	ISO (Nm/kg)
1	2.0	1.8	1.8	1.5	2.1
2	1.3	1.4	1.0	1.1	2.1
3	1.7	1.5	1.3	1.1	1.8
4	1.8	1.7	1.5	1.3	2.2
5	2.9	2.2	2.2	1.6	2.7
6	2.0	1.7	1.4	1.1	2.6
7	2.1	2.0	1.9	1.7	2.6
8	1.7	1.8	1.5	1.3	2.4
9	2.1	2.0	1.4	1.5	2.0
10	2.0	1.5	1.6	1.1	2.3
11	1.7	1.4	1.6	1.2	1.8
12	1.8	1.8	1.7	1.6	1.8
13	1.7	1.5	1.3	1.3	1.9
14	1.3	1.6	1.5	1.5	1.9
15	1.8	1.6	1.4	1.3	1.9
16	1.8	1.6	1.5	1.3	2.4

Subject #	ECC 60 (Nm/kg)	ECC 120 (Nm/kg)	ECC 180 (Nm/kg)	ECC 240 (Nm/kg)
1	3.2	3.1	3.1	3.1
2	3.7	3.6	3.6	3.8
3	3.7	3.5	3.3	3.3
4	3.1	4.0	3.2	3.6
5	4.1	4.3	3.7	3.8
6	3.4	3.5	3.8	3.2
7	3.8	3.6	3.6	3.6
8	3.0	3.1	3.3	3.2
9	3.0	2.5	2.7	2.8
10	3.5	3.7	3.8	3.8
11	2.7	2.6	3.0	2.7
12	4.0	3.0	3.0	2.8
13	3.2	2.9	2.8	3.0
14	2.2	2.7	2.3	2.3
15	3.5	3.8	3.5	3.3
16	3.4	3.0	3.0	3.2

Note: CON = concentric, ISO = isometric, ECC = eccentric; 60, 120, 180, and 240 correspond with the °/s of movement velocity

Table B.9

Female Hamstrings Adjusted Peak Torque

Subject #	CON 60 (Nm/kg)	CON 120 (Nm/kg)	CON 180 (Nm/kg)	CON 240 (Nm/kg)	ISO (Nm/kg)
1	1.6	1.2	1.1	1.1	1.9
2	1.8	1.5	1.2	1.1	2.2
3	1.2	1.2	1.0	1.1	1.3
4	1.9	1.8	1.5	1.4	2.3
5	1.6	1.5	1.4	1.2	1.9
6	1.3	1.1	1.0	0.9	1.8
7	1.0	0.9	0.7	0.4	1.1
8	1.4	1.3	0.9	0.9	1.9
9	1.4	1.4	1.4	1.4	1.7
10	1.6	1.2	1.0	0.9	2.1
Subject #	ECC 60 (Nm/kg)	ECC 120 (Nm/kg)	ECC 180 (Nm/kg)	ECC 240 (Nm/kg)	
1	3.0	3.1	3.0	3.4	
2	2.9	2.9	2.8	2.8	
3	2.3	2.0	2.2	2.1	
4	3.5	3.5	3.5	3.6	
5	2.9	3.1	2.8	3.0	
6	2.2	2.4	2.5	2.5	
7	2.4	2.0	2.0	2.2	
8	2.9	2.3	2.6	2.8	
9	3.1	2.7	3.1	3.0	
10	2.9	2.7	2.9	2.0	

Note: CON = concentric, ISO = isometric, ECC = eccentric; 60, 120, 180, and 240 correspond with the °/s of movement velocity