



## Original Research

## Sex differences in quadriceps rate of torque development within 1 year of ACL reconstruction



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## ABSTRACT

**Objectives:** To investigate the effect of sex on measures of quadriceps strength, rate of torque development, and knee function during the first year following ACLR.

**Design:** Cross-sectional;

**Setting:** University community;

**Participants:** Sixty individuals (29 men) with unilateral ACLR in the last 12 months.

**Main outcome measures:** Participants completed bilateral knee extension maximal voluntary isometric contraction (MVIC, Nm/kg) strength assessments. Rates of torque development ( $\text{Nm} \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$ ) were assessed from contraction initiation to 100 ms (RTD<sub>100</sub>) and from 100 ms to 200 ms after contraction initiation (RTD<sub>200</sub>). The effects of sex MVIC strength, RTD, and limb symmetry were assessed using separate ANCOVAs.

**Results:** Women displayed weaker involved limb (Men =  $2.72 \pm 0.72 \text{ Nm} \cdot \text{kg}^{-1}$ , Women =  $2.01 \pm 0.50 \text{ Nm} \cdot \text{kg}^{-1}$ ,  $p < 0.001$ ) and contralateral limb (Men =  $3.15 \pm 0.52 \text{ Nm} \cdot \text{kg}^{-1}$ , Women =  $2.66 \pm 0.58 \text{ Nm} \cdot \text{kg}^{-1}$ ,  $p < 0.001$ ) MVIC, and slower involved limb RTD<sub>100</sub> (Men =  $8.36 \pm 3.16 \text{ Nm} \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$ , Women =  $6.50 \pm 2.41 \text{ Nm} \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$ ,  $p = 0.01$ ) and RTD<sub>200</sub> (Men =  $9.49 \pm 3.45 \text{ Nm} \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$ , Women =  $9.49 \pm 3.45 \text{ Nm} \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$ ,  $p < 0.001$ ) when compared to men.

**Conclusions:** Within the first year after ACLR, women displayed bilateral quadriceps weakness and slower involved limb quadriceps RTD when compared to men. Specific focus on facilitating quadriceps hypertrophy and improving neural drive to the quadriceps is indicated when treating female patients attempting to make a return to sport after ACLR.

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## 1. Introduction

Persistent quadriceps weakness is common among individuals with ACL reconstruction (ACLR) which is troubling as persistent weakness has been linked to poor patient-reported function (Ithurburn et al., 2018) and greater risk of subsequent ACL injury (Grindem, Snyder-Mackler, Moksnes, Engebretsen, & Risberg, 2016). Consistent with these findings, quadriceps strength has been consistently described as a key criterion for clinical evaluation of physical readiness for return to unrestricted participation in sport following ACLR (Gokeler, Welling, Zaffagnini, Seil, & Padua, 2017;

Grindem et al., 2016; Palmieri-Smith & Lepley, 2015). These recommendations have focused largely on the peak knee extensor torque output (Gokeler et al., 2017) or between limb symmetry (Grindem et al., 2016) measured during an isometric or isokinetic contraction. However, it has been recently hypothesized that in addition to the magnitude of peak torque output, the rate at which torque is developed may provide additional critical information regarding the quality of muscle contact that can be utilized in this decision-making process (Angelozzi et al., 2012). This is because the rate of torque development (RTD) and the magnitude of quadriceps torque independently contribute to the ability of an individual to dissipate lower extremity loading and generate rapid forceful movement during functional tasks which are key to one's ability to effectively participate in sport-related activity (Angelozzi et al., 2012; Pietrosimone et al., 2016a).

Several investigations have confirmed that RTD is predictive of

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vertical ground reaction force and knee joint kinetics during activities of daily living and sport-related movements among individuals with (Pietrosimone et al., 2016a) and without ACLR (Barker, Harry, & Mercer, 2018; Kline, Morgan, Johnson, Ireland, & Noehren, 2015; Pua, Mentiplay, Clark, & Ho, 2017). Accordingly, the clinical importance of assessing RTD in addition to maximal force output is becoming clearer. However, studies that have investigated RTD among individuals with ACLR have not taken participant sex into consideration despite evidence that women with ACLR report worse knee-related function (Kuenze et al., 2019), lesser mass normalized quadriceps strength (Kuenze et al., 2019), and a greater risk of subsequent ACL injury (Paterno, Rauh, Schmitt, Ford, & Hewett, 2014) when compared with men of similar age and physical activity level. The quadriceps muscles are the primary stabilizers of the knee joint during activity and women appear to struggle with persistent quadriceps weakness to a greater degree than men following ACLR (Kuenze et al., 2019). Among young, healthy individuals without history of knee joint injury, there is consistent evidence that women do not generate as great a magnitude of peak isometric knee extensor torque when compared to men which has been hypothesized to be due to sex differences in quadriceps muscle size and contractile properties (Stearns-Reider & Powers, 2018; Wust, Morse, de Haan, Jones, & Degens, 2008). However, this sex difference is not consistently observed when knee extensor RTD has been compared between the sexes (Stearns-Reider & Powers, 2018). Understanding if demographic factors influence the rate at which torque can be developed may provide key clinical context to sex-based differences observed during movement among individuals with ACLR.

Men and women with ACLR are treated similarly throughout the rehabilitation process despite consistent evidence that women are more likely to experience poorer patient-reported and objectively-measured clinical outcomes when compared to men of similar age and activity level (Tan, Lau, Khin, & Lingaraj, 2016). Developing clearer understanding of the extent to which clinical outcomes are influenced by patient sex is essential to the progression of patient-centered rehabilitative care. Therefore, the primary purpose of this study was to determine the effect of participant sex on measures of quadriceps muscle function and patient-reported knee function during the first year following ACLR. We hypothesized that women would report worse knee-related function, display lesser involved limb quadriceps MVIC strength, and display slower involved limb quadriceps RTD when compared to men. The secondary purpose of this study was to determine if quadriceps strength-related outcomes similarly predicted patient-reported knee-related function among men and women with ACLR. We hypothesized that quadriceps MVIC torque and quadriceps RTD<sub>200</sub> would significantly predict knee-related function among both men and women with ACLR.

## 2. Methods

This investigation was part of a larger cohort study in which patients from a single university-based orthopedic sports medicine clinic were enrolled prior to their final follow-up visit which ranged from 5 to 12 months post-ACLR. All reported measures were collected during a single testing session.

### 2.1. Institutional review board approval

This research was approved by the Michigan State University (IRB# 17-1005) Institutional Review Boards for Human Subjects. All participants provided informed written consent, or assent in the case of minors, prior to testing.

### 2.2. Participants

Sixty individuals with a history of ACLR were enrolled in this study (Table 1). All participants were referred to the study team in order to complete a comprehensive return to sport assessment outlined by Grindem et al. (Grindem et al., 2016). Participants were included if they were between the ages of 13 and 40, had a history of unilateral ACLR, had not yet completed their final clinical visit to their orthopaedic surgeon, and were planning to make a full return to pre-injury levels of sport participation. Participants were excluded if they had a history of lower extremity injury within the previous 6 weeks or a neurological condition that may impact lower extremity function. Participants were not excluded if they underwent a meniscal procedure at the time of ACLR. Individuals with previous contralateral ACLR, posterior cruciate ligament reconstruction, or posterolateral corner injury were excluded. Participants completed a knee injury history that included mechanism of injury, sport participation at the time of injury, description of the surgical procedure, and duration of structured rehabilitation (Table 1). Based on the structure of medical system from which the participants were recruited, it was not possible to obtain more detailed information about the number of rehabilitation visits or the specific exercises completed during sessions.

### 2.3. Procedures

Participants completed two patient-reported outcome measures during the data collection session. The Tegner Activity Scale (TAS) was utilized to assess peak pre-injury and post-injury level of physical activity which was rated on a 0–10 scale based on the type and competitive level of activity in which a participant was engaged (Lysholm & Gillquist, 1982). The International Knee Documentation Committee (IKDC) subjective knee evaluation form was used to quantify the impact of knee injury on patient-reported function and activities of daily living (Irrgang et al., 2001; Rossi, Lubowitz, & Guttmann, 2002). The IKDC has strong internal consistency (Cronbach's  $\alpha = 0.77–0.97$ ) and intra-rater reliability (ICC = 0.87–0.98). (Grevnerts, Terwee, & Kvist, 2015).

Following completion of the patient reported outcome measures, participants completed a bilateral assessment of quadriceps maximal voluntary isometric contraction (MVIC) torque which was measured using a multimodal dynamometer (System 4 Pro; Biodex Medical Systems, Inc., Shirley, NY). In all cases, the limb contralateral to the ACLR limb was assessed first. Isometric quadriceps torque data were exported at 2000 Hz using the remote access port and imported to a lab computer via an A/D board (USB-6211, National Instruments, Austin, TX). A customized LabVIEW program recorded the data while providing a real-time visual representation of the participant's torque on a nearby screen to serve as visual feedback during all trials (Luc et al., 2016). To orient participants to the visual and verbal feedback, they were instructed to warm-up by performing three isometric quadriceps contractions at 25, 50 and 75% of their perceived maximal effort for 3 s each.

After the participants became familiar with the testing process, they were asked to perform a single quadriceps MVIC trial. Participants were instructed to kick out as hard and as fast as possible for at least 3 seconds during the trial (Luc et al., 2016). Peak quadriceps MVIC torque (Nm) was documented from the trial and utilized to generate two visual targets on the nearby monitor. The first target line was representative of the participant's peak torque and the second target line represented a value equal to 10% above the peak torque target. Verbal encouragement was also provided by a study team member during strength testing. Previous research has reported an increase in peak quadriceps MVIC torque measurements with use of a visual stimulus (Luc et al., 2016) and assessor verbal

**Table 1**  
Sex-based comparison of demographics and patient-reported outcome measures.

	Men(N = 29)	Women(N = 31)	p-value
Age (years)	20.8 [13.0,36.0]	18.7 [14.0,34.0]	0.14
Height (m)	1.81 ± 0.07	1.72 ± 0.08	<0.001*
Mass (kg)	81.71 ± 17.68	70.97 ± 14.15	0.01*
IKDC Subjective Form Score	84.8 ± 9.2	82.2 ± 9.6	0.10
Pre-injury Tegner Activity Level	9 [6,10]	9 [6,10]	0.41
Current Tegner Activity Level	6 [4,10]	6 [2,10]	0.92
Sport at Time of Injury			
Baseball	6.9%	3.2%	–
Football	34.5%	0.0%	–
Soccer	17.2%	22.6%	–
Track and Field	3.4%	0.0%	–
Hockey	3.4%	0.0%	–
Wrestling	3.4%	0.0%	–
Gymnastics	0.0%	3.2%	–
Basketball	27.6%	58.1%	–
Volleyball	0.0%	9.7%	–
Lacrosse	0.0%	3.2%	–
Mechanism of Injury (% non-contact)	72.4%	83.9%	0.35
Months Since Surgery (mo.)	7.4 [5.0,12.0]	6.9 [4.0,10.0]	0.30
Graft Source (BTB/HSA/Allo)	3/22/4	12/17/2	0.09
Meniscal Repair (% of patients)	37.9%	41.9%	0.80
Meniscectomy (% of patients)	0.0%	6.5%	0.49
Months of Structured Rehabilitation (mo.)	4.2 [1.0,7.0]	4.1 [1.5,9.0]	0.64

BTB = bone-patellar tendon-bone autograft, HAS = hamstring autograft, Allo = allograft, \* indicates a significant between sex difference.

encouragement (Roberts, Kuenze, Saliba, & Hart, 2012). Participants were then asked to complete two more successful quadriceps MVIC trials with 1 min of rest in between. A trial was considered successful if a participant generated peak isometric quadriceps torque equal to or greater than the target established in the preparation trials. This approach has been shown to improve consistency between trials during dynamometer-based strength testing (Luc et al., 2016).

#### 2.4. Data analysis

Peak quadriceps torque, RTD<sub>100</sub>, and RTD<sub>200</sub> were calculated from the final two trials performed during the quadriceps strength assessment. Torque data was filtered through a 2nd order low pass Butterworth filter with a cutoff of 0.10 Hz. Peak quadriceps MVIC torque was calculated as the average peak torque of the last two quadriceps MVIC trials and normalized to body mass (Nm\*kg<sup>-1</sup>). Quadriceps contraction initiation was determined using a moving average filter which identified the first frame in a 50-frame window during which a change in torque greater than 3.0 Nm occurred. This approach to analysis was utilized based on pilot work completed by the investigators which revealed that these parameters resulted in best agreement with visual identification of contraction initiation. RTD<sub>100</sub> was calculated as the slope of the torque x time curve from contraction initiation to 100 ms following contraction initiation (Nm\*kg<sup>-1</sup>\*s<sup>-1</sup>). RTD<sub>200</sub> was calculated as the slope from of the torque x time curve from 100 ms after contraction initiation to 200 ms after contraction initiation (Nm\*kg<sup>-1</sup>\*s<sup>-1</sup>) (Pamukoff et al., 2017). Lastly, limb symmetry indices (LSI, %) were calculated in order to compare quadriceps strength outcomes between the ACLR limb and the contralateral limb:

$$LSI (\%) = \left( \frac{ACLR\ Limb}{Contralateral\ Limb} \right) * 100 \quad (1)$$

#### 2.5. Sample size estimation

An a-priori sample size estimation was completed utilizing recently published involved limb MVIC strength sex comparison

data among individuals with ACLR ( $\eta$  (Grindem et al., 2016) = 0.12)<sup>10</sup> while assuming the use of 2 covariates (age and months since surgery), an acceptable power of 0.80, and an a-priori alpha level of 0.05. Based on this approach, we estimated that a total of 60 participants would be required to successfully detect differences between the sexes in this study. Sample size estimation was completed using G\*Power version 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007).

#### 2.6. Statistical analysis

Descriptive statistics were calculated for all participant characteristics, patient-reported outcomes (Table 1), and quadriceps strength outcomes (Table 2). Distributional normality for quadriceps strength, quadriceps RTD, and IKDC score was tested using the Kolmogorov-Smirnov Goodness-of-Fit test prior to our analysis. This test revealed that quadriceps RTD<sub>100</sub> LSI ( $D = 0.12$ ,  $p = 0.03$ ) was non-normally distributed. Continuous participant demographics were compared between female participants and male participants using independent samples t-tests. Pre- and post-injury Tegner activity score, months of structured rehabilitation, and months since surgery were compared between groups using Mann Whitney *U* tests. Injury mechanism, incidence of meniscal repair, and incidence of meniscectomy were compared between groups using Fischer's exact test. Graft source distribution was compared between groups using a Pearson's  $\chi^2$  test as these data are categorical with more than 2 levels. Quadriceps strength, quadriceps RTD outcomes, and IKDC score were compared between the sexes using separate ANCOVAs while age and months since surgery were utilized as covariates. Partial  $\eta^2$  effect sizes were used to determine the magnitude of standardized mean differences between the sexes. Partial  $\eta^2$  is commonly interpreted using the criteria: small effect  $\geq 0.01$ , medium effect  $\geq 0.06$ , and large effect  $\geq 0.14$ .

Separate stepwise multiple linear regressions were used to assess the association between predictor variables (participant age, months since surgery, involved limb quadriceps strength and RTD outcomes) and patient-reported knee function (IKDC Score) among the total sample, male participants, and female participants. In addition, separate stepwise multiple linear regressions were used

**Table 2**  
Sex-based comparison of quadriceps strength and rate of torque development outcome measures.

		Men (N = 30)	Women (N = 32)	p-value	Effect Size ( $\eta^2$ )
MVIC Torque	Involved Limb (Nm/kg)	2.72 ± 0.72	2.01 ± 0.50	<0.001*	0.38
	Contralateral Limb (Nm/kg)	3.15 ± 0.52	2.66 ± 0.58	<0.001*	0.22
	Limb Symmetry (%)	86.00 ± 15.94	77.22 ± 18.68	0.02*	0.10
RTD <sub>100</sub>	Involved Limb (Nm*kg <sup>-1</sup> *s <sup>-1</sup> )	8.36 ± 3.16	6.50 ± 2.41	0.01*	0.13
	Contralateral Limb (Nm*kg <sup>-1</sup> *s <sup>-1</sup> )	8.41 ± 2.96	7.56 ± 2.43	0.23	0.03
	Limb Symmetry (%)	102.79 ± 29.38	88.62 ± 28.40	0.03*	0.09
RTD <sub>200</sub>	Involved Limb (Nm*kg <sup>-1</sup> *s <sup>-1</sup> )	9.49 ± 3.45	6.70 ± 2.06	<0.001*	0.29
	Contralateral Limb (Nm*kg <sup>-1</sup> *s <sup>-1</sup> )	11.04 ± 2.51	10.28 ± 2.57	0.19	0.03
	Limb Symmetry (%)	86.84 ± 29.58	68.48 ± 26.43	0.002*	0.15

MVIC = maximal voluntary isometric contraction, RTD = Rate of torque development, IKDC = International Knee Documentation Committee subjective knee evaluation form, participant age and months since surgery were utilized as covariates in all analyses, \* indicates a significant between sex difference.

to assess the association between predictor variables (participant age, months since surgery, and RTD outcomes) and involved limb quadriceps strength (peak MVIC torque) among the total sample, male participants, and female participants. All statistical analyses were performed using SPSS statistical software (version 24.0, SPSS Inc., Chicago, IL) and data visualization was performed using the ggplot2 package (Wickham, 2010) in RStudio (RStudio, Inc., Boston, MA). (Team, 2015).

### 3. Results

Female participants were shorter ( $p < 0.001$ ) and had lower body mass ( $p = 0.01$ ) when compared to male participants (Table 1). There were no significant sex differences for injury or surgical characteristics, pre-injury ( $p = 0.57$ ) or post-injury ( $p = 0.76$ ) Tegner activity level, or IKDC score ( $p = 0.10$ ). Female participants displayed lesser involved limb ( $p < 0.001$ ) and contralateral limb ( $p < 0.001$ ) quadriceps MVIC torque (Fig. 1) and quadriceps MVIC LSI ( $p = 0.02$ ) (Table 2). Female participants also displayed lesser involved limb quadriceps RTD<sub>100</sub> ( $p = 0.01$ ), involved limb RTD<sub>200</sub> ( $p < 0.001$ ; Fig. 2), RTD<sub>100</sub> LSI ( $p = 0.03$ ), and RTD<sub>200</sub> LSI ( $p = 0.002$ ) (Fig. 2).

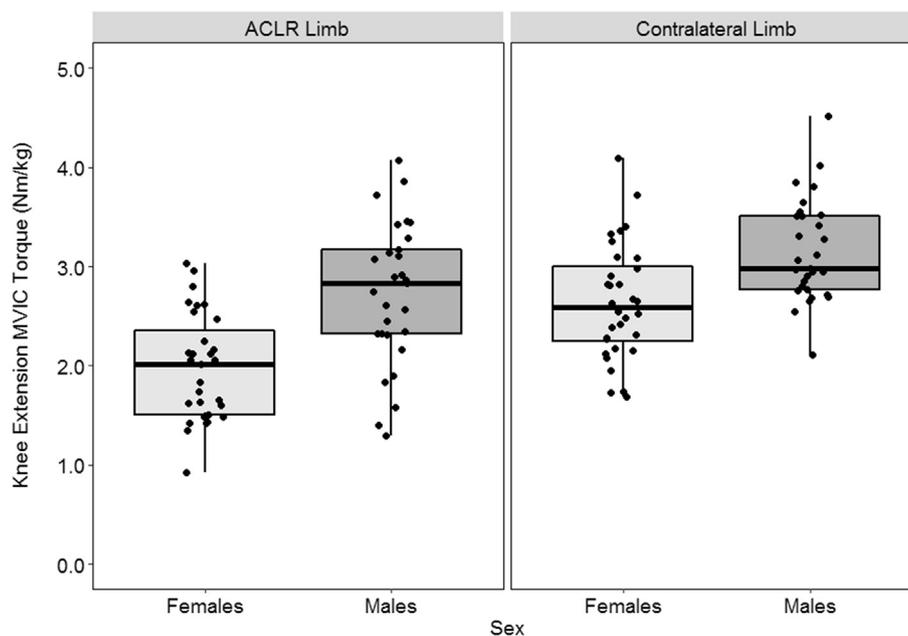
Linear regression revealed that quadriceps RTD<sub>200</sub> successfully

predicted 16.0% of the variance ( $p < 0.001$ ) in IKDC score among the complete sample (Table 3). When limited to male participants, quadriceps RTD<sub>200</sub> was the only variable included in the regression model which predicted 27.7% of the variance in IKDC score ( $p = 0.001$ ). When limited to female participants, there were no significant predictors of IKDC score.

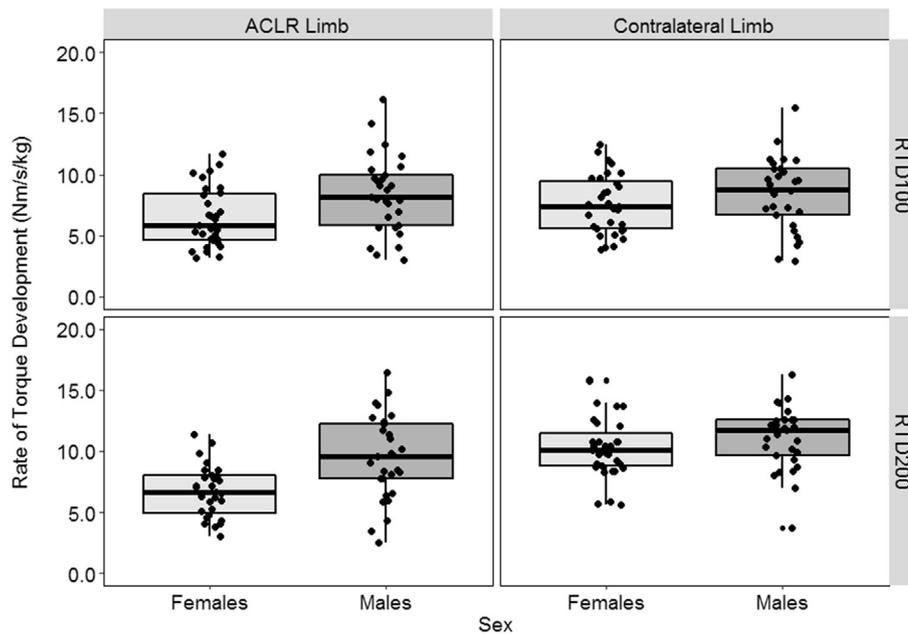
Linear regression also revealed that involved limb quadriceps RTD<sub>200</sub> and RTD<sub>100</sub> successfully predicted 54.8% of the variance ( $p < 0.001$ ) in involved limb quadriceps MVIC torque among the total sample (Table 4). When limited to male participants, quadriceps RTD<sub>100</sub> and months since surgery predicted 49.8% of the variance in involved limb quadriceps MVIC torque ( $p < 0.001$ ) while involved limb quadriceps RTD<sub>200</sub> and RTD<sub>100</sub> successfully predicted 63.4% of the variance in involved limb quadriceps MVIC torque ( $p < 0.001$ ) among female participants.

### 4. Discussion

The primary purpose of this study was to investigate the effects of participant sex on quadriceps RTD and MVIC strength among individuals preparing for return to sport following ACLR. We found that women with ACLR displayed weaker involved limb ( $\eta^2 = 0.38$ ) and contralateral limb ( $\eta^2 = 0.22$ ) quadriceps MVIC and involved



**Fig. 1.** Sex and limb comparison of quadriceps MVIC torque among individuals with ACLR. Female participants with ACLR display lesser normalized quadriceps MVIC torque in the ACLR limb ( $p < 0.001$ ) and the contralateral limb ( $p < 0.001$ ) when compared with male participants with ACLR.



**Fig. 2.** Sex and limb comparison of RTD<sub>100</sub> and RTD<sub>200</sub> among individuals with ACLR. Female participants with ACLR display slower RTD<sub>100</sub> ( $p = 0.01$ ) and RTD<sub>200</sub> ( $p < 0.001$ ) in the ACLR limb when compared with male participants with ACLR.

**Table 3**

Sex-based prediction of knee-related function using demographic, surgical, and strength factors.

	Variable Entered	Standardized $\beta$ Coefficients	Adjusted R <sup>2</sup>	P value
All Participants	Quadriceps RTD <sub>200</sub>	0.415	0.160	<0.001
Male Participants	Quadriceps RTD <sub>200</sub>	0.545	0.277	0.001
Female Participants	No Variables Entered			

MVIC = maximal voluntary isometric contraction, RTD = Rate of torque development.

**Table 4**

Sex-based prediction of knee extension MVIC torque using demographic, surgical, and RTD factors.

	Variable Entered	Standardized $\beta$ Coefficients	Adjusted R <sup>2</sup>	P value
All Participants	Quadriceps RTD <sub>200</sub>	0.472	0.548	<0.001
	Quadriceps RTD <sub>100</sub>	0.336		
Male Participants	Quadriceps RTD <sub>100</sub>	0.553	0.498	<0.001
	Months since surgery	-0.380		
Female Participants	Quadriceps RTD <sub>200</sub>	0.338	0.634	<0.001
	Quadriceps RTD <sub>100</sub>	0.564		

MVIC = maximal voluntary isometric contraction, RTD = Rate of torque development.

limb quadriceps RTD<sub>100</sub> ( $\eta^2 = 0.13$ ) and RTD<sub>200</sub> ( $\eta^2 = 0.29$ ) when compared to men with ACLR. However, when measures of limb symmetry were considered, only quadriceps RTD<sub>100</sub> ( $\eta^2 = 0.09$ ) and RTD<sub>200</sub> ( $\eta^2 = 0.15$ ) were found to significantly differ between the sexes with women displaying significantly greater asymmetry as compared to men. These findings indicate that a sex disparity is present in quadriceps function among individuals who are preparing for a return to sport following ACLR and that measures of limb symmetry may not be sensitive enough to identify these important clinical deficits during this critical period of recovery time.

In this study, women displayed significant bilateral quadriceps weakness and slower involved limb RTD when compared to male participants despite similar age, time since surgery, pre-injury activity level, and graft source distribution (Table 1). These outcomes indicate that women may be experiencing a greater magnitude of change in quadriceps muscle structure and neural dysfunction

resulting greater quadriceps dysfunction across the reported outcomes reported (Table 2). More specifically, RTD<sub>200</sub> has been reported to be an indicator of the functional capacity of type IIa and type IIx muscle fibers within a muscle group (Hsieh, Indelicato, Moser, Vandenborne, & Chmielewski, 2015). Recent work by Noehren et al. has established that individuals experiencing involved limb quadriceps weakness following ACLR experience significant quadriceps muscle atrophy driven by a reduction in the percentage of muscle cross-sectional area made up of type IIa and type IIx muscle fibers (Noehren et al., 2016). While subsequent work is needed to establish whether the magnitude of change in fiber type distribution differs between men and women, our findings point toward a potential sex difference in the quadriceps structural response to ACLR that may be leading to disparities in quadriceps RTD<sub>200</sub> and quadriceps MVIC torque. This is in contrast to previous work that indicates a lack of difference in knee extensor RTD (Stearns-Reider & Powers, 2018) but is consistent with work

that has reported significant differences in body mass normalized quadriceps MVIC torque among healthy young men and women without a history of knee injury (Wust et al., 2008). Our findings indicate that women may also be experiencing a significantly worse reduction in neural drive to the quadriceps muscle which has been shown to cause slower RTD<sub>100</sub> and reduced muscle strength (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002). This is further supported by the significant roles that both RTD<sub>100</sub> ( $\beta = 0.338$ ) and RTD<sub>200</sub> ( $\beta = 0.564$ ) play in determining quadriceps MVIC torque among female participants ( $R^2 = 0.634$ , Table 4) which is in contrast to the model developed for male participants which is limited to significant contributions from RTD<sub>100</sub> ( $\beta = 0.553$ ) and months since surgery ( $\beta = -0.380$ ,  $R^2 = 0.498$ ). Based on the importance of quadriceps strength and quadriceps RTD in restoring normal knee joint kinematics and kinetics following ACLR, our findings indicate that women may need additional targeted rehabilitation which restores muscle size and enhances neural drive to quadriceps during the terminal phases of rehabilitation and beyond. Specific evidence-based approaches may include heavy resistance training and exercise including eccentric components, such as plyometrics, both of which have been shown to promote muscle hypertrophy and enhance neural drive to the quadriceps muscle group (Aagaard et al., 2002; Lepley, 2014; Lepley, Wojtys, & Palmieri-Smith, 2015).

Symmetry in lower extremity function, and more specifically in quadriceps strength, has been identified as a key indicator of physical readiness for return to sport and incidence of second ACL injury within two years of ACLR (Ithurburn et al., 2018; Grindem et al., 2016). Accordingly, it is important to understand whether sex influences symmetry in quadriceps function among individuals preparing for return to sport following ACLR given the fact that women are less likely to make a successful return to sport and are more likely to experience a second ACL injury after return (Paterno et al., 2014; Ardern, 2015). In this study, men and women displayed comparable LSI for quadriceps MVIC but not RTD<sub>100</sub> or RTD<sub>200</sub> (Table 2). In terms of quadriceps MVIC strength, previous literature is inconsistent regarding sex differences in symmetry; however a recent investigation including 230 participants within one year of ACLR did indicate that women may be likely to experience lesser asymmetry when compared to men despite also displaying weaker involved limb quadriceps (Kuenze et al., 2019). This indicates that women may be weaker bilaterally within 1 year of ACLR which is consistent with our findings. It is important to note that, on average, both men and women fell below the clinically recommended 90.0% LSI for quadriceps MVIC indicating that both men and women appear to be experiencing clinically meaningful strength asymmetry as they prepare for return to sport.

Regarding the RTD findings, as previously noted, women displayed slower involved limb quadriceps RTD<sub>100</sub> and RTD<sub>200</sub> when compared to men indicating that they were experiencing both muscle fiber capacity and neural drive to the quadriceps muscle. Interestingly, when evaluating the magnitude of asymmetry of men in this study, they displayed near perfect symmetry for RTD<sub>100</sub> and significantly lesser asymmetry for RTD<sub>200</sub> as compared to women despite no significant differences between the groups for contralateral RTD outcomes. This indicates that contralateral muscle fiber capacity and neural drive may be comparable between men and women prior to return to sport following ACLR; however, this does not appear to be the case for the involved limb. It is important to note that there is not currently established acceptable LSI for RTD-related outcomes and therefore it is difficult to evaluate whether or not RTD symmetry is an important indicator of readiness for sport or potential risk for subsequent ACLR injury as quadriceps symmetry has been shown to be in previous studies (Grindem et al., 2016; Ithurburn et al., 2018). Currently, there are also a lack of

normative values for RTD symmetry among young and healthy individuals which makes it challenging to contextualize our findings relative to what would be expected among those without knee injury. However, in a limited body of literature in this area, it has been reported that both men and women do not display significant between limb differences in RTD in the absence of lower extremity injury (Szpala, Rutkowska-Kucharska, & Stawiany, 2015). Continued evaluation of involved limb RTD and RTD symmetry among men and women with ACLR throughout the process of rehabilitation and return to sport, as well as comparison of these metrics between individuals with and without a history of knee injury, may provide key insight into the relative importance of maximal strength versus RTD among this at risk population.

There is a wealth of evidence to support the relationship between quadriceps function and patient-reported knee function among individuals with ACLR (Pietrosimone et al., 2013, 2016b; Kuenze et al., 2015; Lepley, 2015a, 2015b). However, the vast majority of these studies have included heterogeneous populations and have not taken sex into consideration when quantifying the strength of this association despite recent evidence that indicates that women experience greater involved limb quadriceps weakness following ACLR (Kuenze et al., 2019). Accordingly, we attempted to determine if quadriceps MVIC strength and RTD were predictive of patient-reported knee function (IKDC score) and if this association was similar when our participants were dichotomized based on sex. Among the total sample, involved limb quadriceps RTD<sub>200</sub>, but not quadriceps MVIC strength or RTD<sub>100</sub> was able to predict only 15.7% of the variance in IKDC score (Table 3). These findings are counter to a recent investigation by Lepley et al. who indicated that quadriceps MVIC strength and knee joint pain assessed at a similar timepoint as that included in this paper predicted 74.0% if the variance in IKDC score (Lepley, Pietrosimone, & Cormier, 2018). However, it should be noted that participants in that study indicated that they had already made a return to activity which was not the case for participants in this investigation. Predictors of IKDC score were not consistent when the sample was dichotomized based on sex. Among men, quadriceps RTD<sub>200</sub> was the only significant predictor of IKDC score and this single variable was able to explain nearly half of the variance in IKDC score (46.3%; Table 3). Conversely, there were no significant quadriceps-related predictors of IKDC among women in this study. These findings indicate that while quadriceps function plays a key role in knee stabilization and functional performance for men and women, the relationship between quadriceps function and perceived knee-related function may be influenced by sex. A recent review of the literature surrounding sex-based differences in psychological response to ACLR indicated that women may process and respond to ACL injury and rehabilitation from ACLR differently than men including experiencing lesser self-efficacy, greater anxiety regarding the impact of injury on daily life, and lesser physical self-worth following rehabilitation (Sims & Mulcahey, 2018). While it is unlikely that psychological factors would explain the entirety of difference between the sexes, the lack of consideration of psychological outcomes is a limitation and should be considered in subsequent investigations given the strong correlation ( $r = 0.59$ ) between psychological readiness for sport and IKDC score among young individuals within 2 years of ACLR (Sadeqi et al., 2018). Based on our findings, restoration of quadriceps function remains important for successful return to sport-related activity among individuals with ACLR but it may be necessary to consider sex specific predictors of patient-reported function when developing specific approaches to intervention tasked with optimizing patient-centered clinical outcomes.

There are several key limitations that should be considered when interpreting the results of this study. This study investigated sex differences in quadriceps RTD and MVIC torque among a

relatively heterogenous (age and rehabilitation experience) cohort of patients who were tested prior to clearance for return to unrestricted sport participation. As such, it is unclear if participants experienced improvement in either of the primary outcomes as a result of increased intensity of activity upon return to sport. Similarly, as this was a cross-sectional design limited to a between group comparison, it remains unclear if the sex differences observed in this study were related to subsequent functional limitations, failure to fully return to sport, or second ACL injury. This study design did not allow for comparison to a group of matched healthy controls which would have helped to clarify the interaction between participant sex and injury status. In the case of both limitations, the literature in this area would be bolstered through the design and execution of a prospective study in which quadriceps function was monitored following return to sport and the utility of this measure in identify individuals at risk for poor clinical outcomes was further evaluated. Lastly, this study was limited to the evaluation of key outcomes during an isometric contraction which is not a comprehensive descriptor of quadriceps muscle function. Evaluation of sex differences in concentric and eccentric quadriceps function would aid in developing a more nuanced and specific understanding of functional limitations experienced by both sexes.

## 5. Conclusion

Women who had not yet returned to sport following ACLR display weaker quadriceps muscles bilaterally and slower involved limb quadriceps RTD when compared to men of similar demographics and time since surgery. This is despite an inconsistency in limb symmetry sex differences which have commonly been utilized as primary criterion for physical readiness for return to sport. These findings not only highlight that women appear to experience significant limitations in quadriceps function at the terminal phases of rehabilitation but also that relying solely on measures of limb symmetry may not be sufficient to identify these critical clinical deficits prior to clearance for return to sport. It is essential that researchers and clinicians work to develop interventional approaches that are effective in restoring quadriceps strength and RTD and that the effectiveness of these interventions is evaluated among men and women with ACLR in order to promote optimal clinical outcomes regardless of sex.

## Conflicts of interest

The authors declare no conflicts of interest for this work.

## Ethical approval

All research related activities were approved by the Institutional Review Boards and Michigan State University (Human Research Protection Program #17-1005), and all participants provided written informed consent prior to study participation.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.pts.2019.04.008>.

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