Sex Differences in the Power-Duration Relationship for Dynamic Knee Extension are Largely Explained by Muscle Size

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ABSTRACT

Although males generally outperform females in absolute exercise tasks, it is unclear whether these differences persist for small muscle mass exercise when accounting for muscle size and anatomical factors. The purpose of this study was to compare the power-duration relationship for dynamic knee extension exercise between healthy males (n=12) and females (n=12) matched for maximal aerobic fitness relative to fat-free mass ($\dot{V}O_2$max: 59.5±7.9 vs. 59.2±6.0 mL·kgFFM^{-1}·min^{-1}; p=0.921). Participants completed four constant work rate tests to measure critical power (CP) and the curvature constant (W′). Using magnetic resonance imaging (MRI), quadriceps volume was assessed to estimate and control for muscle mass, and the patellar tendon moment arm (PTMA) was measured to estimate quadriceps force. Males demonstrated a significantly greater CP (p=0.003), CP torque (p<0.001), CP quadriceps force (p=0.003), and W′ (p=0.036) compared to females. No sex difference in CP measures remained after controlling for quadriceps mass (p>0.05). An interaction between sex and quadriceps mass regarding W′ (p=0.036) revealed a positive association in males (p<0.001) but not in females (p=0.926). After adjusting for quadriceps mass, whole-body and single-leg aerobic fitness were related to CP (p<0.05). Maximal quadriceps force was related to W′ (p=0.044), but strength did not appear to influence CP independently of quadriceps mass (p>0.05). Overall, sex differences in absolute CP were largely explained by muscle size as opposed to an innate difference between male and female muscle, and variability in CP was not independently related to strength or PTMA.

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Keywords: Critical power; Small muscle mass exercise; Endurance; Biological sex; Aerobic fitness; Isolated muscle mass

New & Noteworthy

In males and females matched for aerobic fitness [maximal oxygen uptake normalized to fat-free mass (FFM)], dynamic knee extension critical power (CP) was greater in males, but after adjusting for differences in quadriceps muscle size, CP was similar between sexes. These findings indicate that sex differences in small muscle mass performance result from differences in muscle size, not innate differences in muscle endurance capacity.

Introduction

As much of our knowledge originates from male-dominated research populations (1–3), biological sex differences in relative exercise performance are not fully understood. On average, males can generate greater muscular forces and sustain higher absolute work rates during exercise than females (4–6). This advantage stems primarily from being larger and leaner, and possessing a greater total hemoglobin mass (7,8), larger lungs and airways (9,10) and a greater glycolytic capacity (11), among other factors. These physiological differences may not translate to greater relative performance when size differences are controlled (12) or greater performance for small muscle mass exercise (i.e., isolated muscle mass exercise), where central factors play a smaller role (13). Indeed, females have a more oxidative skeletal muscle profile with a greater proportion of type I muscle fibres (14,15) and may achieve greater oxygen extraction at the muscle (8,16,17), suggesting a greater relative capacity for aerobic metabolism (11,18) and potentially a higher sustainable exercise intensity at the level of the muscle. Whether these physiological differences translate to greater relative exercise performance for small muscle mass exercise, independent of anatomical differences, is unclear.

The critical intensity model can be applied to small muscle mass exercise to compare muscle-specific performance between sexes. As the boundary between the heavy and severe exercise intensity domains, the critical intensity of exercise is a valuable indicator of endurance performance (19–24). While we previously showed the relative critical intensity was not different between males and females for cycling (12), the determinants of exercise performance differ for whole-body and small muscle mass exercise. Specifically, small muscle mass exercise may be limited by factors such as skeletal muscle mitochondrial content (25,26), vascular function (27), and oxygen diffusive transport (28) rather than central factors (13), although both central and peripheral systems contribute to aerobic capacity in an integrative manner (29). In line with a potential peripheral advantage, females were suggested to have a higher relative critical torque than males (30). While we recently reported no significant difference in this parameter when males and females were matched for aerobic fitness relative to fat-free mass (FFM) (26), experimental limitations warranted additional research. Both studies normalized critical torque to maximal voluntary contraction – conflating endurance and strength parameters – and neither study accounted for sex differences in muscle size and patellar tendon moment arm (PTMA) lengths (31,32), which influence the translation of muscle force output to external work (33). It remains unclear whether sex differences in absolute endurance performance are attributable to mechanical factors (i.e., muscle size or leverage) rather than intrinsic physiological differences within the muscle itself. Further, dynamic exercise may offer a greater ecological validity for understanding endurance performance. Thus, investigating sex differences in dynamic knee extension CP while considering anatomical factors may provide deeper insights into potential differences in skeletal muscle performance between males and females.

The primary objective of this study was to investigate the extent to which biological sex inherently influences the power-duration relationship, independently of anatomical factors, for dynamic knee extension exercise in healthy males and females matched for aerobic fitness. The secondary objective was to explore the extent to which strength influenced the power-duration relationship. We hypothesized that (i) while males would achieve a higher absolute CP than females, the sex difference in knee extension torque at CP would be abolished when adjusted for differences in quadriceps mass, (ii) when also accounting for PTMA, estimates of quadriceps force at CP would be greater in females when adjusted for quadriceps mass, compensating for a shorter PTMA, and (iii) strength would be positively associated with W′.

Methods

Ethical Approval

This study received institutional ethical approval from the University of Calgary Conjoint Health Research Ethics Board (REB24-0351) and was conducted according to the Declaration of Helsinki. Prior to participation, participants were informed of the study's purpose, procedures, and potential benefits and risks before providing written, informed consent.

Participants

An effect size of 1.6 was conservatively chosen based on the results of sex differences in PTMA from Dandridge et al. (31), yielding a required sample size of 20 participants (G*Power; Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany). While 27 (13 male, 14 female) healthy, recreationally active participants aged 18-40 were recruited to participate in this study, data from three participants (one male, two female) were excluded due to irregularities in the intensity-duration relationship, indicating inconsistent or submaximal performance across trials. Thus, data from 24 participants (12 male, 12 female) were used for analysis.

All participants were performing ≥3 hours of moderate to vigorous physical activity per week (Get Active Questionnaire; Canadian Society of Exercise Physiology, Ottawa, ON, Canada) and were free of contraindications for magnetic resonance imaging (MRI) (Alberta Health Services, Edmonton, AB, Canada). Participants were asked to refrain from fatiguing or high-intensity exercise 24 hours before exercise testing sessions to minimize the interference of incomplete recovery with outcome measures.

Experimental Design

In this cross-sectional study, participants completed seven laboratory visits over ~3 weeks. During the first visit, participants underwent a dual-energy x-ray absorptiometry (DXA) scan to assess body composition, performed strength testing to investigate relationships between maximal strength and the power-duration parameters, and practiced dynamic knee extension exercise protocols, including constant work rate and step-incremental testing. For Visit 2, participants completed a cycling ramp-incremental exercise test to characterize aerobic fitness and continued with familiarization to dynamic knee extension exercise, performing multiple bouts of constant, high-intensity exercise. During Visit 3, participants completed a single-leg dynamic knee extension step-incremental exercise test. During Visits 4 and 5, participants performed dynamic knee extension exercise to task failure multiple times to establish the power-duration relationship. During Visit 6, the force output associated with CP was assessed. Finally, knee and thigh MRI scans were performed during Visit 7 to assess anatomical determinants of force production (muscle size and PTMA length).

Data Collection and Analysis

Body Composition

DXA scans were performed to assess body composition, using a Lunar iDXA device (General Electrical Healthcare, Chicago, IL). Specifically, whole-body FFM was determined as the difference between body mass and fat mass.

Maximal Strength

For quadriceps maximal voluntary contraction (MVC) assessments, participants were secured to a custom-made chair dynamometer with hip and knee flexion angles of 90° and performed submaximal isometric contractions prior to completing three maximal efforts. Isometric force, sampled continually at a frequency of 2000 Hz using an ankle strap connected to an S-type load cell (Omega Engineering, Norwalk, CT), was converted to an amplified analog voltage with a strain-gauge amplifier (COND-SGA; Sensy S.A., Charleroi, Belgium) and recorded using PowerLab hardware (ADInstruments, Bella Vista, Australia) and data acquisition software (LabChart 8; ADInstruments). The highest force from the three trials was recorded as MVC. The distance between the participant's lateral femoral epicondyle and the center of the strap was measured to calculate knee extension torque.

Whole-Body Aerobic Fitness

Participants completed a 20 W·min $^{-1}$ ramp-incremental test on an electromagnetically-braked cycle ergometer (Velotron; Racermate Inc., Seattle, WA) to assess whole body maximal oxygen uptake ($\dot{V}O_2$max), as well as peak power output (PPO). Expired gases were collected in a mixing chamber and measured in 10-s intervals using a metabolic cart (Quark CPET; Cosmed, Rome, Italy). A gas mixture of known concentrations (15.90 % O_2, 4.95 % CO_2, balance N_2) was used to calibrate gas analyzers prior to testing, and the turbine flowmeter was calibrated with a 3-L syringe. Participants cycled for 5 min at 50 W prior to a 20 W·min $^{-1}$ ramp-incremental test at a consistent, self-selected cadence between 80-100 rpm while blinded to all test parameters. The test was terminated when a participant could no longer maintain a cadence above 60 rpm despite strong verbal encouragement. Whole-body $\dot{V}O_2$max was calculated as the highest 30-s average $\dot{V}O_2$ observed during the cycling ramp-incremental test. $\dot{V}O_2$max was expressed as an absolute value (L·min $^{-1}$), relative to body mass (mL·kgBM $^{-1}$·min $^{-1}$), and relative to FFM (mL·kgFFM $^{-1}$·min $^{-1}$) to ensure males and females were matched for aerobic fitness (34). A chest strap monitor (T31 Coded Transmitter; Polar, Kempele, Finland) was used to record heart rate (HR).

Dynamic Knee Extension Testing

All single-leg dynamic knee extension testing was completed on a knee extension ergometer (KEE 2000; Technavance, Austin, TX), shown in Figure 1B, using the same experimental setup for all measures. The ergometer chair kept participants seated upright with a hip flexion angle of ~90°. An abdominal belt limited movement of the upper body while arms rested on armrests. The foot of the tested leg was secured in a binding with two buckling straps, over the proximal and distal aspects of the foot. The foot binding was connected to a crank arm rod that turned the attached flywheel with each knee extension motion, allowing the leg to be passively returned to its starting position between each active extension phase. The non-tested leg rested on an adjustable platform with a relaxed knee flexion angle of 90°. The ergometer incorporated five sensors (two calibrated load cells, an optical encoder, a photo microsensor, and a magnetic switch), with signals received by an embedded microprocessor to measure exercise parameters instantaneously, including force, cadence, and PO, at a frequency of 8-10 Hz. Data were transmitted to PowerLab hardware and recorded with LabChart software (ADInstruments).

All knee extension exercise testing was performed at a fixed cadence of 40 rpm, and participants were provided continuous visual feedback of their average cadence (over the three previous contraction cycles) as well as an auditory metronome. Investigators monitored average PO (5-s average) and made manual adjustments to the flywheel resistance. Participants were instructed to maintain a steady contraction cadence as close to 40 rpm as possible and to allow the knee to passively flex after each contraction to minimize hamstring activation. Surface electromyography (EMG) from the vastus lateralis and biceps femoris muscles of the tested leg was recorded as an index of muscle activation throughout the test using a Dual Bio Amp system, PowerLab, and LabChart software (ADInstruments), as previously described (35). While not analyzed, investigators monitored muscle activation and verbally prompted participants to avoid use of the hamstrings if a burst of activity was observed between extensions.

To account for quadriceps work performed against the direction of the flywheel (i.e., negative work), and to minimize the impact of hamstring contractions contributing to calculations of positive work, instantaneous PO was recorded as an absolute value only where a positive (i.e., anterior) force was measured at the foot (Figure 1A).

Single-Leg Aerobic Fitness

A step-incremental protocol was used to assess single-leg peak oxygen uptake ($\dot{V}O_2$peak). Participants completed 5 min of dynamic knee extension exercise at 5 W, immediately after which a step-incremental protocol was initiated increasing at a rate of 3 W·min^{-1}. Participants were blinded to their elapsed time and PO throughout the incremental protocol. If participants dropped their cadence below 37 rpm, investigators verbally encouraged them to recover to 40 rpm. The test was terminated when cadence continued to decrease despite strong verbal encouragement, or if average PO suddenly decreased with cadence. Expired gases were collected with a metabolic cart, as described above, to measure single-leg $\dot{V}O_2$peak and PPO, determined as the highest 30-s average PO observed during the step-incremental test.

Power-Duration Relationship

Participants performed dynamic knee extension exercise to failure at four different constant work rate intensities to determine CP and the curvature constant (W′; Figure 1C). Each trial utilized an identical testing procedure using the experimental setup described above for the knee extension ergometer. Participants first completed a standardized knee extension warmup at 5 W for 5 min. Resistance was then gradually increased over approximately 10 s until the target power output for the CP trial was reached, with the trial continuing at this constant work rate until failure (as described above). Participants were blinded to the time elapsed and the target work rate of each trial. Two trials, interspersed with 20 min of rest, were completed in each of Visits 4 and 5. The first trial was performed between 85-95% of single-leg PPO. Subsequent trial intensities were pseudo-randomized and adjusted based on time to task failure from previous trials, guided by linear regression of the developing work-time relationship to obtain four trials distributed between 2-15 min (36). CP and W′ were represented by the slope and y-intercept, respectively, of the linear regression between total work and duration (20,36).

Magnetic Resonance Image Acquisition

Axial MRI scans of the dominant leg were performed using a 3T scanner (SIGNA Ultra High Performance; General Electrical Medical Systems, Chicago, IL) to measure quadriceps volume. Subjects laid in a supine position, with hip and knee joints fully extended, with two overlapping air coils to provided coverage of the entire region of interest, from 5 cm below the iliac crest proximally to 10 cm below the apex of the patella distally. An iterative decomposition of water and fat with echo asymmetry and least-squares estimation (IDEAL-IQ) sequence was performed with the following parameters: TR=6.752 ms, TE=3.1 ms, averages: 1.5, image matrix=256 x 256 x 150, flip angle=3°, slice thickness=2.0 mm, and in-plane resolution=0.9375 x 0.9375 mm. MRI scans of the upper and lower femur regions were acquired separately due to field of view limitations. An overlapping region was captured to facilitate subsequent image stitching. A sagittal scan of the knee was then performed using a T1-weighted fast spin echo (T1 FSE) to capture PTMA length, with the following sequence parameters: TR= 787 ms, TE= 5.756 ms, averages=2, image matrix =512x512x90, flip angle=111°, slice thickness=1.5 mm, in-plane resolution=0.547 mm x 0.547 mm.

Magnetic Resonance Image Processing

Upper and lower IDEAL-IQ femur scans were aligned utilizing global positioning data, and, where necessary, three-dimensional rigid registration was applied to correct any misalignment. For the overlapping regions, a distance-weighted blending approach was implemented to stitch images together and minimize signal drop-off and preserve anatomical continuity. Processing and registration were performed using open-source tools (Python v13.3; Python Software Foundation, Wilmington, DE; SimpleITK 2.4.1). Manual segmentation of water-intensity maps across the full femur was performed to measure total quadriceps volume using open-source tools (ITK-SNAP). The four muscles in the quadriceps group were captured under a single segmentation label in their entirety. Manual segmentation was completed by investigators for every fifth slice, then interpolation was applied in the axial plane to fill in the remaining slices (Figure 1D). The result was visualized in a three-dimensional rendering used to locate errors in the interpolation, which were corrected manually. The volume output for the entire segmentation label was taken as quadriceps volume, and the volumes obtained by two independent raters were averaged and taken as the final quadriceps volume. There was excellent inter-rater reliability (ICC(3,2): 0.997, $p<0.001$). To simplify reporting, quadriceps muscle mass was estimated by multiplying the measured muscle volume by 1.06 $kg \cdot L^{-1}$, the density of mammalian skeletal muscle tissue (37).

PTMA was measured in anatomical position as the distance between the tibio-femoral contact point and the mid-line of the patellar tendon, drawn perpendicular to the line of the tendon (38,39), in ITK-SNAP using scans of the knee in the sagittal plane obtained from the T1 FSE sequence (Figure 1D).

Quadriceps Muscle Force Output

A 1-min average of steady dynamic knee extension contractions, over the entire movement cycle, at the target PO (average within 0.1 W from calculated CP across 1 min) from a 5-min bout was used to measure the anterior force output during contractions at CP. Knee joint angle was measured continuously using an electronic goniometer (Biometrics Ltd, Newport, UK) secured to the thigh parallel to the femur and the lower leg parallel to the tibia, with each end placed at an equal distance from the tibio-femoral cleft (32). The distance between the knee (femoral lateral epicondyle) and the height of the force sensor at the ankle was measured, then multiplied by the average force measured at CP to calculate average knee torque at CP. This torque was then divided by the measured PTMA to estimate the average force output by the quadriceps (40). The relevant lengths and forces in this calculation are depicted in Figure 1E.

Statistical Analysis

Data were first assessed for normality using normality plots and the Shapiro-Wilk test, and homogeneity of variance using Levene's test. To assess inter-rater reliability for quadriceps mass, an intraclass correlation coefficient was calculated using a two-way mixed effects model for average measures. Analysis of covariance (ANCOVA) was used with sex as a fixed factor to explore sex differences in relationships between quadriceps mass and the power-duration parameters, as well as sex differences in these variables after adjusting for quadriceps mass as a covariate. Data were first assessed for linearity with the covariate using Pearson's correlations, normality of residuals using normality plots and the Shapiro-Wilk test, and homogeneity of variance using Levene's test. Outliers were defined as values with unusually large residuals, indicating poor model fit, or values greater than three standard deviations from the group mean. Outliers were excluded from final analyses. Homogeneity of regression slopes was evaluated, and where significant interaction effects were identified, distinct parameter estimates for males and females were reported. If no significant interaction was present, a simplified ANCOVA model without the interaction term was run, and overall effects were reported. To facilitate comparisons to previous studies, power-duration parameters were scaled to quadriceps mass. Relationships were assessed for linearity and homogeneity, and student's independent t tests were performed between males and females for these ratio-scaled data where appropriate.

To investigate potential determinants of the power-duration relationship, Pearson's correlations were calculated to assess relationships between pairs of variables in the overall sample, with partial correlations used to assess these relationships after controlling for quadriceps mass.

Statistical analysis was performed using SPSS (V29; IBM, Armonk, NY) and Prism 8 (GraphPad, San Diego, CA). Statistical significance was accepted where $p<0.05$, and all data are presented throughout the manuscript as mean [standard deviation].

Results

Participant Characteristics and Aerobic Fitness

Participant characteristics are shown in Table 1. Males had a significantly greater height, body mass (BM), and FFM compared to females. Whole-body (cycling) $\dot{V}O_2$max was used to characterize and match relative aerobic fitness between males and females. Males had a significantly greater absolute $\dot{V}O_2$max and PPO compared to females; however, $\dot{V}O_2$max and PPO expressed relative to BM and FFM were not significantly different between sexes. Males also had a significantly greater quadriceps mass and PTMA than females (Table 1).

In the single-leg maximal step-incremental test, absolute $\dot{V}O_2$peak was significantly higher in males (1.44 [0.23] $L \cdot min^{-1}$) than females (1.16 [0.24] $L \cdot min^{-1}$; $p=0.008$). PPO was also significantly higher in males (45.5 [6.8] W) than females (34.5 [5.2] W; $p<0.001$). Quadriceps mass was significantly associated with $\dot{V}O_2$peak ($r=0.611$, $p=0.002$) and PPO ($r=0.831$, $p<0.001$). ANCOVA models using quadriceps mass as a covariate showed no sex difference in regression slopes for $\dot{V}O_2$peak ($F(3,20)=1.485$, $p=0.237$) and PPO ($F(3,20)=0.108$, $p=0.745$), so simplified ANCOVA models without the interaction term were run. When adjusted for quadriceps mass, there was no sex difference in single-leg $\dot{V}O_2$peak ($F(2,21)=0.417$, $p=0.525$) or

PPO (F(2,21)= 0.510, p=0.483). Regression slopes are plotted in Figure 2, and estimated marginal means are shown in Figure 3.

Sex Differences in the Power-Duration Relationship

The fit of intensity-duration relationships was excellent using the linear work-time regression (R^2: 0.999 [0.001], range: 0.997-1.000). One outlier for W′ was removed prior to all analyses due to the extreme raw value (+3.36 standard deviations from the mean) and the resulting violation of normality and equal variance assumptions. As shown in Table 2, relative to females, males had a significantly greater absolute CP, torque at CP, quadriceps force at CP, and W′; however, none of these variables differed between sexes when scaled to quadriceps mass where appropriate (Table 2). There was also no significant difference in CP expressed relative to PPO between males (74.5 [10.8] %PPO) and females (73.0 [6.6] %PPO; p=0.678).

Quadriceps mass was significantly correlated with CP (r=0.659 p<0.001), torque at CP (r=0.724, p<0.001), quadriceps force at CP (r=0.678, p<0.001), and W′ (r=0.731, p<0.001) in the overall sample. The ANCOVA analysis using quadriceps mass as a covariate revealed a sex difference in regression slopes for W′ (F(3,19)=5.086, p=0.036), though not for any measure of CP (p>0.05; Table 3; Figure 2). Parameter estimates showed that males demonstrated a greater slope in the relationship between quadriceps mass and W′ than females, where W′ increased significantly with quadriceps mass in males (β=1.3, p<0.001) but not in females (β=−0.05, p=0.926). With no interaction between sex and quadriceps mass for variations of CP, simplified ANCOVA models with no interaction term were run. When adjusted using quadriceps mass as a covariate, there was no sex difference in any of these variables (p>0.05), though each showed a significant main effect of quadriceps mass (p<0.05) (Table 3; Figure 3).

Determinants of the Power-Duration Relationship

Correlations between variables and all variations of CP were similar, so only relationships with CP are reported. Prior to adjusting for quadriceps mass as a covariate, positive associations with CP were observed for PTMA, aerobic fitness (whole-body and single-leg $\dot{V}O_2max/\dot{V}O_2peak$ and PPO), and maximal strength (MVC torque and quadriceps force). Partial correlations controlling for quadriceps mass showed that significant relationships with CP were maintained only for whole-body and single-leg aerobic fitness measures (Table 4).

In terms of potential determinants of W′, single-leg peak PPO and maximal strength (MVC torque and quadriceps force) were positively correlated with W′ prior to controlling for quadriceps mass. After controlling for quadriceps mass using partial correlations, only the positive relationship between MVC quadriceps force and W′ persisted (Table 4). Significant negative associations between whole-body aerobic fitness measures and W′ (Table 4), as well as between CP and W′ ($r=-0.657$, $p<0.001$), were observed only after controlling for quadriceps mass.

Discussion

The main findings of this study were that (i) when matched for aerobic fitness and adjusting for quadriceps mass as a covariate or scaling to quadriceps mass, males and females did not differ in terms of single-leg knee extension CP; (ii) quadriceps mass was a significant predictor of W′ in males but not females; and (iii) aerobic fitness and muscle strength appear to be determinants of the power-duration relationship, independent of muscle size. Overall, variation in knee extension CP was independent of sex when accounting for differences in quadriceps mass, though sex differences were observed regarding the capacity to translate quadriceps mass into severe-intensity work.

Biological Sex and the Power-Duration Relationship

When matched for $\dot{V}O_2$max relative to FFM, males achieved a higher absolute CP and W′ than females, which was expected given their generally larger body size and quadriceps muscle mass (41,42), conferring performance advantages by enabling greater muscular force production and work rates. This finding is consistent with previous studies of fitness-matched males and females for cycling exercise, where males also demonstrated superior absolute performance (12,43). In a previous investigation using isometric knee extension, we surprisingly did not observe a significantly greater absolute critical torque in males, but males demonstrated a larger absolute W′ than females (26). Given the association between muscle mass and absolute performance measures in the present investigation, quadriceps mass was included as a covariate in all relevant analyses to account for its influence. While not intentional, matching for whole-body aerobic fitness resulted in no difference between sexes for single-leg $\dot{V}O_2$peak after adjusting for quadriceps mass as a covariate.

In the present study, we found no sex difference in single-leg CP (including the torque and estimated quadriceps force output at CP) when adjusted for (or scaled to) quadriceps mass, indicating that biological sex did not account for additional variability beyond that explained by quadriceps mass, which was larger in males (32,44). This result suggests that sex differences in absolute single-leg CP are attributable to muscle size rather than inherent differences in muscle physiology, consistent with recent evidence against sex-specific metabolic mechanisms of fatigue or fatigue resistance (45). This finding also aligns with studies reporting a lack of sex differences for the critical intensity (12,26), with the exception of a recent study (46). While Wilkins et al. (2025), reported greater relative end-test power for females compared to males, that study estimated FFM from skinfolds and estimated CP with a 3-min all-out test, which are less precise than the methods used in our studies. To our knowledge, this is the first study to investigate sex differences in the relationship between quadriceps mass and dynamic knee extension performance, although quadriceps mass was previously suggested to be a determinant of absolute single-leg CP in males (47). To mitigate the confounding effects of differences in body size and composition between males and females, previous studies have expressed the critical intensity relative to MVC for isometric knee extension (26) and to FFM for cycling (12). Such ratio scaling assumes strictly proportional relationships between variables, which can be problematic in drawing meaningful conclusions (48). Expressing the critical intensity relative to MVC conflates two distinct physiological capacities – muscle endurance and strength – which are not necessarily related. Scaling to FFM, although meaningful biologically, similarly assumes a proportional relationship between whole-body FFM and the critical intensity, with a shared slope and intercept between males and females. When evaluating sex differences in performance, examining relationships between variables may provide more meaningful insight than ratio-based comparisons (48). Nevertheless, the results in the present study were similar whether we adjusted variables for quadriceps mass or scaled variables to quadriceps mass.

Males exhibited a higher torque and estimated quadriceps force output at CP, although these differences were also abolished when considering quadriceps mass. This finding contradicted our hypothesis that females would exhibit greater quadriceps force at CP after adjusting for quadriceps mass due to their shorter PTMA, and that PTMA would meaningfully contribute to sex differences in CP. While we expected differences in CP torque to be eliminated after adjusting for quadriceps mass, we anticipated that the significantly shorter PTMA in females would impose a mechanical disadvantage (31), requiring greater quadriceps force outputs to generate knee extension torques comparable to males. While accounting for PTMA reduced the numerical gap in CP torque between sexes, the lack of statistical significance for either variable suggests that other physiological factors likely contribute to within-sex variability in CP torque for a given quadriceps mass. Nevertheless, our observed agreement between CP, torque, and estimated quadriceps force output indicates that the shorter female PTMA does not explain sex differences in absolute endurance performance, allowing females to generate CP torques not significantly different from males when accounting for quadriceps mass.

In contrast to CP, we demonstrated a sex difference in the relationship between quadriceps mass and W′. That quadriceps mass was associated with W′ in males but not in females disagrees with a previous study that reported no relationship between quadriceps mass and W′ in males (47), though quadriceps mass was estimated using surface measurements in that study. Although ratio scaling was inappropriate in the present study due to the observed sex difference in this relationship, a previous study from our laboratory found that sex differences in W′ for cycling persisted even when normalized to FFM (12). This result, as well as the sex difference in the relationship between quadriceps mass and W′ observed in the present study, may be partly explained by established associations between type IIx fibre proportion and W′ (12,26), with an advantage for males due to an expected higher proportion of IIx fibres and a greater glycolytic capacity per unit of muscle mass (15).

Determinants of the Power-Duration Relationship

Whole-body $\dot{V}O_2$max and PPO were related to single-leg CP, and this association persisted after adjusting for quadriceps mass. This finding suggests that individuals with a higher aerobic capacity tend to achieve a higher CP independent of muscle mass, meaning that inter-individual differences in CP reflect true physiological variation in aerobic function, aligning with our hypothesis. The association between whole-body aerobic fitness and single-leg CP is likely underpinned by peripheral aerobic function, as the influence of central factors is reduced with small muscle mass exercise (13). Similarly, single-leg $\dot{V}O_2$peak and PPO were significantly associated with CP independent of quadriceps mass, reinforcing the interpretation that peripheral mechanisms contribute substantially to the capacity to perform sustained exercise, with dynamic knee extension CP serving as an indicator of muscle endurance (49). Although prior evidence has pointed to mitochondrial respiration as a key limiting factor for single-leg exercise (25), dynamic knee extension CP may be constrained by blood flow (27), or diffusive oxygen transport (28), highlighting the need for further investigation using well-controlled, in vivo studies. Lastly, MVC was not associated with CP after adjusting for quadriceps mass, which is in agreement with previous research showing that single-leg CP is related to quadriceps muscle mass (estimated via surface measurements) but not to muscle strength (47).

Our data supported the hypothesis that maximal strength may play a role in the power-duration relationship by linking intrinsic muscle force-generating capacity, independent of muscle size and leverage, to the capacity to perform anaerobic work. W′ was related to MVC torque and estimated MVC quadriceps force, suggesting that strength may influence the anaerobic work capacity. When adjusting for quadriceps mass, MVC torque was no longer significantly associated with W′ (p=0.073) whereas the relationship with quadriceps force persisted. We suggest that W′ may be related to the force-generating capacity of the quadriceps when isolated from leverage effects observed at the joint whereas MVC torque may be confounded by variability in PTMA length, making it less specific to the physiological underpinnings of W′ than quadriceps force. This result is consistent with the lack of association between strength and single-leg W′ observed previously (47) and is supported by previous evidence of an association between strength and W′ for cycling (50,51), suggesting that W′ may be influenced by intrinsic neuromuscular properties in addition to muscle mass. The association between W′ and single-leg PPO was abolished after adjusting for quadriceps mass, indicating that muscle size confounds the relationship between local aerobic capacity and the ability to perform work above CP. This finding is consistent with the established characterization of W′ as an anaerobic property (20,36).

After adjusting for quadriceps mass (itself correlated with PTMA), the significant relationships between PTMA and CP, including CP torque, did not persist. This finding suggests that PTMA does not significantly influence W′ and that PTMA does not uniquely impact CP or CP torque beyond its covariance with quadriceps mass. Regarding CP, the absence of an independent PTMA effect may help to explain the lack of sex difference in CP torque observed between sexes despite a similar quadriceps force as discussed above.

Significant negative relationships emerged between CP and W′ when examined independent of quadriceps mass. This result suggests that muscle size contributes positively to each of these variables and suppresses their underlying relationships. When muscle mass is held constant, individuals display a trade-off between aerobic and anaerobic capacities.

Experimental Considerations

Several experimental considerations and limitations may impact the contextualization and generalizability of our findings. The cross-sectional design used in this study allowed us to examine relationships between variables but limited our ability to draw causal inferences. Pulmonary gas exchange and ventilatory responses during single-leg exercise should be interpreted with caution, as it cannot be confirmed that these measures fully reflect the underlying metabolic demands of the isolated muscle group. The calculation of quadriceps force output provided in this study represents an average estimate, integrating a dynamic force output with a static PTMA measure. PTMA is a dynamic property, and variability introduced by sex, muscle activity, and contraction type makes instantaneous PTMA difficult to accurately determine throughout the range of motion (31,52–55); therefore, its precise joint angle-specific quantification should be a goal for future studies aiming to determine quadriceps force output. In addition, this study did not quantify knee flexion torques produced via coactivation of the knee flexors. Nevertheless, previous research suggests that inter-individual differences in PTMA are roughly preserved across the range of motion (56,57), and that coactivation effects are similar across sexes (32,58), increasing our confidence in the present interpretations of our results. Finally, this study did not control for hormonal fluctuations across the menstrual cycle, although previous studies have demonstrated no effect of menstrual phase on the power-duration relationship for cycling (59), and a similar reliability across days for single-leg performance in both sexes (26).

Conclusions

In fitness-matched males and females, CP was associated with quadriceps muscle mass and aerobic fitness rather than sex or strength. Despite a shorter PTMA in females, estimated CP quadriceps force remained similar, suggesting that sex differences in knee structure do not impose a significant impact on CP. A sex-specific relationship emerged for W′, with males demonstrating a greater capacity to translate muscle mass into high-intensity work; however, W′ correlated with maximum estimated quadriceps force in the full sample, supporting a general link between contractile properties of the muscle and anaerobic work capacity. These findings suggest a lack of innate difference in skeletal muscle endurance between male and female muscle, highlighting the central role of anthropometric factors in exercise performance. Future studies are needed to determine the extent to which similar muscle endurance reflects a common physiological response to exercise across sexes.

Data Availability

The data supporting the findings of this study are included within the figures or are available as supporting information published with the paper online.

Additional information

Graphical abstract was created with BioRender.com

Competing Interests

The authors have no competing interests to declare.

Author Contributions

All aspects of this experiment were completed in the Molecular, Environmental, and Exercise Physiology (MEEP) Laboratory at the University of Calgary or the Alberta Children's Hospital (MRI only). All authors contributed to the conception and design of the work and the acquisition, analysis, and/or interpretation of the data. RSG and MJM wrote the first draft of the manuscript, and all other authors critically revised the manuscript for intellectual content. All authors approved the final version of the manuscript and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy and integrity of any part of the work are appropriately investigated and resolved. All persons listed as authors qualify for authorship, and all those who qualify for authorship are listed.

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References

1. Costello JT, Bieuzen F, Bleakley CM. Where are all the female participants in Sports and Exercise Medicine research? Eur J Sport Sci. 2014;14(8):847–51. doi:10.1080/17461391.2014.911354 PubMed PMID: 24766579.

2. Cowley E, Olenick A, Mcnulty K, Ross E. “Invisible Sportswomen”: The Sex Data Gap in Sport and Exercise Science Research. Women in Sport and Physical Activity Journal. 2021 Oct 1;29:1–6. doi:10.1123/wspaj.2021-0028

3. Elliott-Sale KJ, Minahan CL, de Jonge XAKJ, Ackerman KE, Sipilä S, Constantini NW, et al. Methodological Considerations for Studies in Sport and Exercise Science with Women as Participants: A Working Guide for Standards of Practice for Research on Women. Sports Med. 2021 May;51(5):843–61. doi:10.1007/s40279-021-01435-8 PubMed PMID: 33725341; PubMed Central PMCID: PMC8053180.

4. Bishop P, Cureton K, Collins M. Sex difference in muscular strength in equally-trained men and women. Ergonomics. 1987 Apr 1;30(4):675–87. doi:10.1080/00140138708969760 PubMed PMID: 3608972.

5. Lindle RS, Metter EJ, Lynch NA, Fleg JL, Fozard JL, Tobin J, et al. Age and gender comparisons of muscle strength in 654 women and men aged 20-93 yr. J Appl Physiol (1985). 1997 Nov;83(5):1581–7. doi:10.1152/jappl.1997.83.5.1581 PubMed PMID: 9375323.

6. Miller AEJ, MacDougall JD, Tarnopolsky MA, Sale DG. Gender differences in strength and muscle fiber characteristics. Europ J Appl Physiol. 1993 Mar 1;66(3):254–62. doi:10.1007/BF00235103

7. Kontro H, Caswell AM, Tripp TR, Ajayi OO, MacInnis MJ. Sex-based differences in hematological values after normalization to body mass or fat-free mass in adults matched for aerobic fitness. Appl Physiol Nutr Metab. 2024 Nov 1;49(11):1517–28. doi:10.1139/apnm-2024-0148 PubMed PMID: 39047300.

8. Murphy WG. The sex difference in haemoglobin levels in adults — Mechanisms, causes, and consequences. Blood Reviews. 2014 Mar 1;28(2):41–7. doi:10.1016/j.blre.2013.12.003

9. Dominelli PB, Ripoll JG, Cross TJ, Baker SE, Wiggins CC, Welch BT, et al. Sex differences in large conducting airway anatomy. J Appl Physiol (1985). 2018 Sep 1;125(3):960–5. doi:10.1152/japplphysiol.00440.2018 PubMed PMID: 30024341; PubMed Central PMCID: PMC6335094.

10. Schwartz J, Katz SA, Fegley RW, Tockman MS. Sex and Race Differences in the Development of Lung Function. Am Rev Respir Dis. 1988 Dec;138(6):1415–21. doi:10.1164/ajrccm/138.6.1415

11. Tarnopolsky MA. Sex Differences in Exercise Metabolism and the Role of 17-Beta Estradiol. Medicine & Science in Sports & Exercise. 2008 Apr;40(4):648. doi:10.1249/MSS.0b013e31816212ff

12. Caswell AM, Tripp TR, Kontro H, Edgett BA, Wiley JP, Lun V, et al. The influence of sex, hemoglobin mass, and skeletal muscle characteristics on cycling critical power. Journal of Applied Physiology. 2024 Jul;137(1):10–22. doi:10.1152/japplphysiol.00120.2024

13. Andersen P, Adams RP, Sjøgaard G, Thorboe A, Saltin B. Dynamic knee extension as model for study of isolated exercising muscle in humans. J Appl Physiol (1985). 1985 Nov;59(5):1647–53. doi:10.1152/jappl.1985.59.5.1647 PubMed PMID: 4066596.

14. Nuzzo JL. Sex differences in skeletal muscle fiber types: A meta-analysis. Clinical Anatomy. 2024;37(1):81–91. doi:10.1002/ca.24091

15. Simoneau JA, Lortie G, Boulay MR, Thibault MC, Thériault G, Bouchard C. Skeletal muscle histochemical and biochemical characteristics in sedentary male and female subjects. Can J Physiol Pharmacol. 1985 Jan;63(1):30–5. doi:10.1139/y85-005 PubMed PMID: 3986689.

16. Murphy WG, Tong E, Murphy C. Why do women have similar erythropoietin levels to men but lower hemoglobin levels? Blood. 2010 Oct 14;116(15):2861–2. doi:10.1182/blood-2010-07-294595

17. Wiebe CG, Gledhill N, Warburton DE, Jamnik VK, Ferguson S. Exercise cardiac function in endurance-trained males versus females. Clin J Sport Med. 1998 Oct;8(4):272–9. doi:10.1097/00042752-199810000-00004 PubMed PMID: 9884791.

18. Roepstorff C, Thiele M, Hillig T, Pilegaard H, Richter EA, Wojtaszewski JFP, et al. Higher skeletal muscle alpha2AMPK activation and lower energy charge and fat oxidation in men than in women during submaximal exercise. J Physiol. 2006 Jul 1;574(Pt 1):125–38. doi:10.1113/jphysiol.2006.108720 PubMed PMID: 16600998; PubMed Central PMCID: PMC1817798.

19. Collins J, Leach O, Dorff A, Linde J, Kofoed J, Sherman M, et al. Critical power and work-prime account for variability in endurance training adaptations not captured by $\dot{V}$o2max. Journal of Applied Physiology. 2022 Oct;133(4):986–1000. doi:10.1152/japplphysiol.00344.2022

20. Jones AM, Vanhatalo A, Burnley M, Morton RH, Poole DC. Critical power: implications for determination of V˙O2max and exercise tolerance. Med Sci Sports Exerc. 2010 Oct;42(10):1876–90. doi:10.1249/MSS.0b013e3181d9cf7f PubMed PMID: 20195180.

21. Joyner MJ. Modeling: optimal marathon performance on the basis of physiological factors. Journal of Applied Physiology. 1991 Feb;70(2):683–7. doi:10.1152/jappl.1991.70.2.683

22. Poole DC, Burnley M, Vanhatalo A, Rossiter HB, Jones AM. Critical Power: An Important Fatigue Threshold in Exercise Physiology. Med Sci Sports Exerc. 2016 Nov;48(11):2320–34.

doi:10.1249/MSS.0000000000000939 PubMed PMID: 27031742; PubMed Central PMCID: PMC5070974.

23. Smyth B, Muniz-Pumares D. Calculation of Critical Speed from Raw Training Data in Recreational Marathon Runners. Med Sci Sports Exerc. 2020 Dec;52(12):2637–45. doi:10.1249/MSS.0000000000002412 PubMed PMID: 32472926; PubMed Central PMCID: PMC7664951.

24. Vanhatalo A, Jones AM, Burnley M. Application of critical power in sport. Int J Sports Physiol Perform. 2011 Mar;6(1):128–36. doi:10.1123/ijspp.6.1.128 PubMed PMID: 21487156.

25. Gifford JR, Garten RS, Nelson AD, Trinity JD, Layec G, Witman MAH, et al. Symmorphosis and skeletal muscle $\dot{V}O2$ max : in vivo and in vitro measures reveal differing constraints in the exercise-trained and untrained human. J Physiol. 2016 Mar 15;594(6):1741–51. doi:10.1113/JP271229 PubMed PMID: 26614395; PubMed Central PMCID: PMC4799962.

26. McDougall RM, Tripp TR, Frankish BP, Doyle-Baker PK, Lun V, Wiley JP, et al. The influence of skeletal muscle mitochondria and sex on critical torque and performance fatiguability in humans. The Journal of Physiology. 2023;601(23):5295–316. doi:10.1113/JP284958

27. Dorff A, Bradford C, Hunsaker A, Atkinson J, Rhees J, Leach OK, et al. Vascular dysfunction and the age-related decline in critical power. Experimental Physiology. 2024;109(2):240–54. doi:10.1113/EP091571

28. Goulding RP, Marwood S. Interaction of Factors Determining Critical Power. Sports Med. 2023 Mar 1;53(3):595–613. doi:10.1007/s40279-022-01805-w

29. Wagner PD. Determinants of maximal oxygen consumption. J Muscle Res Cell Motil. 2023 Jun;44(2):73–88. doi:10.1007/s10974-022-09636-y PubMed PMID: 36434438.

30. Ansdell P, Brownstein CG, Škarabot J, Hicks KM, Howatson G, Thomas K, et al. Sex differences in fatigability and recovery relative to the intensity–duration relationship. The Journal of Physiology. 2019;597(23):5577–95. doi:10.1113/JP278699

31. Dandridge O, Garner A, Amis AA, Cobb JP, van Arkel RJ. Variation in the patellar tendon moment arm identified with an improved measurement framework. Journal of Orthopaedic Research. 2022;40(4):799–807. doi:10.1002/jor.25124

32. O'Brien TD, Reeves ND, Baltzopoulos V, Jones DA, Maganaris CN. In vivo measurements of muscle specific tension in adults and children. Experimental Physiology. 2010;95(1):202–10. doi:10.1113/expphysiol.2009.048967

33. Hori M, Suga T, Terada M, Miyake Y, Nagano A, Isaka T. Torque-producing capacity is affected by moment arm in the human knee extensors. BMC Research Notes. 2020 Jul 20;13(1):343. doi:10.1186/s13104-020-05182-3

34. Tripp TR, Kontro H, Gillen JB, MacInnis MJ. Fit for comparison: controlling for cardiorespiratory fitness in exercise physiology studies of sex as a biological variable. The Journal of Physiology. 2025;603(8):2219–30. doi:10.1113/JP287735

35. Zhang J, Iannetta D, Alzeeby M, MacInnis MJ, Aboodarda SJ. Exercising muscle mass influences neuromuscular, cardiorespiratory, and perceptual responses during and following ramp-incremental cycling to task failure. American Journal of Physiology-Regulatory, Integrative and Comparative Physiology. 2021 Aug;321(2):R238–49. doi:10.1152/ajpregu.00286.2020

36. Hill DW. The Critical Power Concept. Sports Medicine. 1993 Oct 1;16(4):237–54. doi:10.2165/00007256-199316040-00003

37. Zuo J, Zhou D, Zhang L, Zhou X, Gao X, Hou W, et al. Comparison of bioelectrical impedance analysis and computed tomography for the assessment of muscle mass in patients with gastric cancer. Nutrition. 2024 May 1;121:112363. doi:10.1016/j.nut.2024.112363

38. Blazevich AJ, Coleman DR, Horne S, Cannavan D. Anatomical predictors of maximum isometric and concentric knee extensor moment. Eur J Appl Physiol. 2009 Apr;105(6):869–78. doi:10.1007/s00421-008-0972-7 PubMed PMID: 19153760.

39. Miyake Y, Suga T, Otsuka M, Tanaka T, Misaki J, Kudo S, et al. The knee extensor moment arm is associated with performance in male sprinters. Eur J Appl Physiol. 2017 Mar 1;117(3):533–9. doi:10.1007/s00421-017-3557-5

40. de Brito Fontana H, Herzog W. Vastus lateralis maximum force-generating potential occurs at optimal fascicle length regardless of activation level. Eur J Appl Physiol. 2016 Jun 1;116(6):1267–77. doi:10.1007/s00421-016-3381-3

41. Chorley A, Bott RP, Marwood S, Lamb KL. Physiological and anthropometric determinants of critical power, W’ and the reconstitution of W’ in trained and untrained male cyclists. Eur J Appl Physiol. 2020 Nov;120(11):2349–59. doi:10.1007/s00421-020-04459-6 PubMed PMID: 32776219; PubMed Central PMCID: PMC7560916.

42. Miura A, Endo M, Sato H, Sato H, Barstow TJ, Fukuba Y. Relationship between the curvature constant parameter of the power-duration curve and muscle cross-sectional area of the thigh for cycle ergometry in humans. Eur J Appl Physiol. 2002 Jul;87(3):238–44. doi:10.1007/s00421-002-0623-3 PubMed PMID: 12111284.

43. Kontro H, Bertagnolli C, Murias JM, MacInnis MJ. Impairment in maximal lactate steady state after carbon monoxide inhalation is related to training status. Exp Physiol. 2022 Nov;107(11):1265–82. doi:10.1113/EP090642 PubMed PMID: 36029041.

44. Behan FP, Maden-Wilkinson TM, Pain MTG, Folland JP. Sex differences in muscle morphology of the knee flexors and knee extensors. PLoS One. 2018;13(1):e0190903. doi:10.1371/journal.pone.0190903 PubMed PMID: 29360834; PubMed Central PMCID: PMC5779647.

45. Laginestra FG, Broxterman RM, Iannetta D, Lewis MT, Kofoed JS, Craig JC, et al. The influence of biological sex on the metabolic basis of skeletal muscle fatigue in vivo. J Physiol. 2025 Nov;603(22):6881–94. doi:10.1113/JP289709 PubMed PMID: 40961462.

46. Wilkins BW, Fisher KG, Flood EF, Heenan LJ, Matthews IR. Sex differences in the maximal metabolic steady state of fitness-matched women and men. Journal of Applied Physiology. 2025 Feb;138(2):612–22. doi:10.1152/japplphysiol.00655.2024

47. Le Chevalier JM, Vandewalle H, Thépaut-Mathieu C, Pujo M, Le Natur B, Stein JF. Critical power of knee extension exercises does not depend upon maximal strength. Eur J Appl Physiol. 2000 Mar 1;81(6):513–6. doi:10.1007/s004210050077

48. Allison DB, Paultre F, Goran MI, Poehlman ET, Heymsfield SB. Statistical considerations regarding the use of ratios to adjust data. Int J Obes Relat Metab Disord. 1995 Sep;19(9):644–52. PubMed PMID: 8574275.

49. Le Chevalier JM, Vandewalle H, Thépaut-Mathieu C, Stein JF, Caplan L. Local critical power is an index of local endurance. Eur J Appl Physiol. 2000 Jan 1;81(1):120–7. doi:10.1007/PL00013784

50. Kordi M, Menzies C, Parker Simpson L. Relationship between power–duration parameters and mechanical and anthropometric properties of the thigh in elite cyclists. Eur J Appl Physiol. 2018 Mar 1;118(3):637–45. doi:10.1007/s00421-018-3807-1

51. Sawyer BJ, Stokes DG, Womack CJ, Morton RH, Weltman A, Gaesser GA. Strength Training Increases Endurance Time to Exhaustion During High-Intensity Exercise Despite No Change in Critical Power. The Journal of Strength & Conditioning Research. 2014 Mar;28(3):601. doi:10.1519/JSC.0b013e31829e113b

52. Chen Z, Franklin DW. Muscle Moment Arm–Joint Angle Relations in the Hip, Knee, and Ankle: A Visualization of Datasets. Ann Biomed Eng. 2025 May 9. doi:10.1007/s10439-025-03735-w

53. Herzog W, Read LJ. Lines of action and moment arms of the major force-carrying structures crossing the human knee joint. J Anat. 1993 Apr;182(Pt 2):213–30. PubMed PMID: 8376196; PubMed Central PMCID: PMC1259832.

54. Hosseinzadeh S, Barzegari A, Taghipour M, Mehr Aein R, Gholinia H. Changes of the Patellar Tendon Moment rm Length in Different Knee Angles: A Biomechanical in Vivo Study. Arch Bone Jt Surg. 2020 Sep;8(5):641–5. doi:10.22038/abjs.2020.42551.2158 PubMed PMID: 33088867; PubMed Central PMCID: PMC7547162.

55. Tsaopoulos DE, Baltzopoulos V, Richards PJ, Maganaris CN. In vivo changes in the human patellar tendon moment arm length with different modes and intensities of muscle contraction. Journal of Biomechanics. 2007;40(15):3325–32. doi:10.1016/j.jbiomech.2007.05.005

56. Krevolin JL, Pandy MG, Pearce JC. Moment arm of the patellar tendon in the human knee. Journal of Biomechanics. 2004 May 1;37(5):785–8. doi:10.1016/j.jbiomech.2003.09.010

57. Tsaopoulos DE, Baltzopoulos V, Maganaris CN. Human patellar tendon moment arm length: measurement considerations and clinical implications for joint loading assessment. Clin Biomech (Bristol). 2006 Aug;21(7):657–67. doi:10.1016/j.clinbiomech.2006.02.009 PubMed PMID: 16624460.

58. Wu R, Delahunt E, Ditroilo M, Lowery M, De Vito G. Effects of age and sex on neuromuscular-mechanical determinants of muscle strength. AGE. 2016 May 17;38(3):57. doi:10.1007/s11357-016-9921-2

59. James JJ, Leach OK, Young AM, Newman AN, Mpongo KL, Quirante JM, et al. The exercise power-duration relationship is equally reproducible in eumenorrheic female and male humans. J Appl Physiol (1985). 2023 Feb 1;134(2):230–41. doi:10.1152/japplphysiol.00416.2022 PubMed PMID: 36548510.

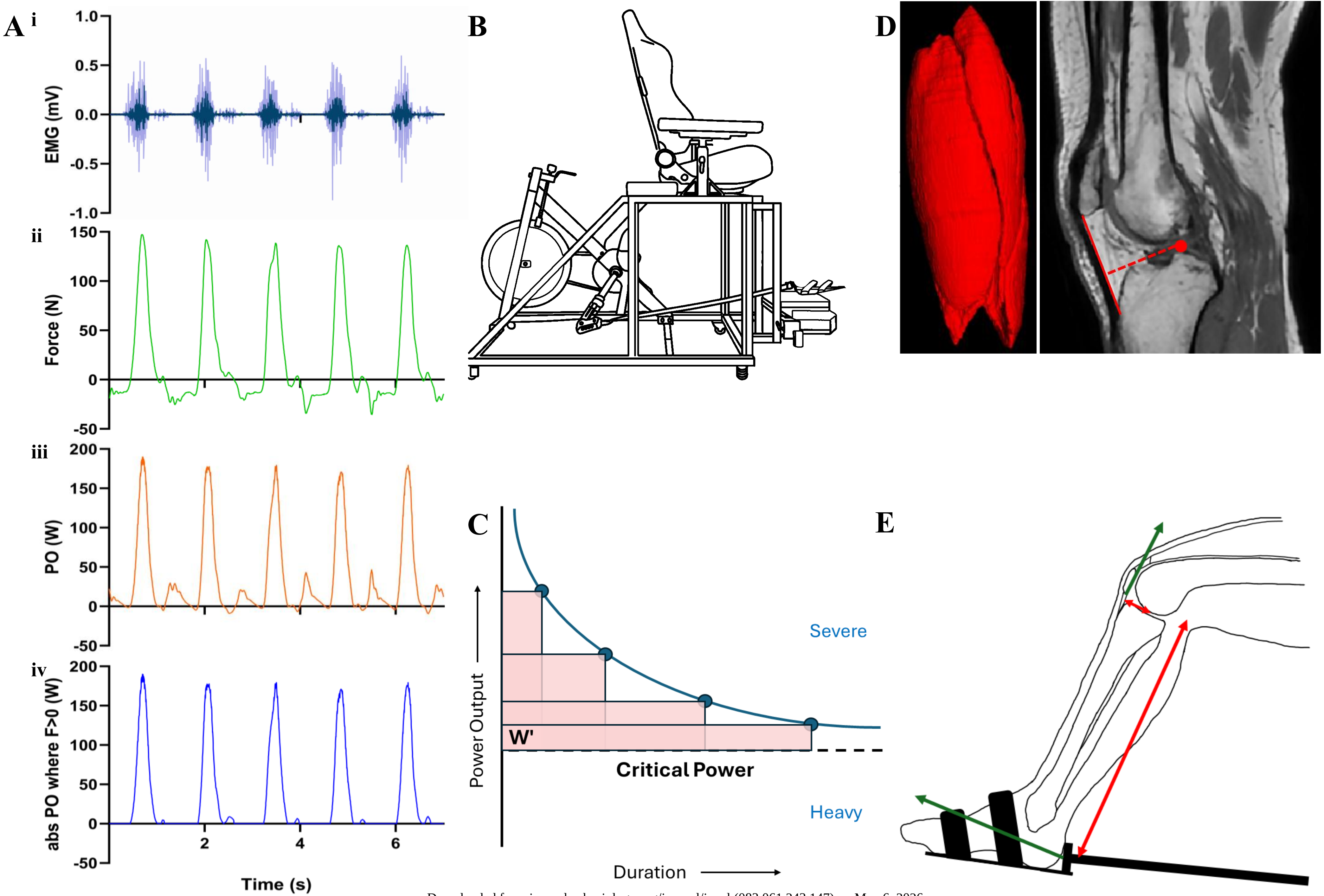
Figure Captions

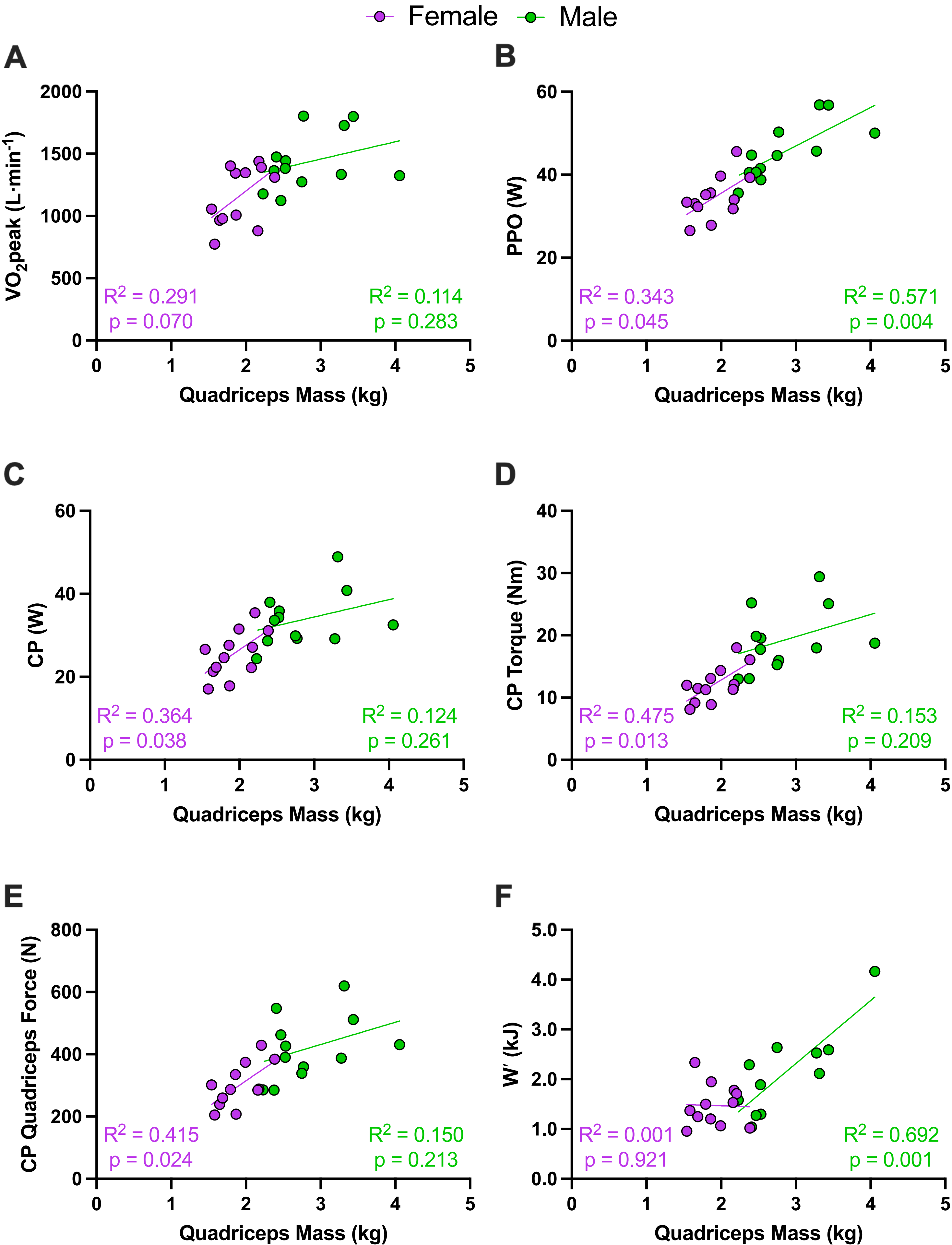
Figure 1: Dynamic knee extension experimental setup and overview. (A) Representative data acquisition trace. (i) Raw surface electromyography (EMG) signals from the vastus lateralis (light purple) and biceps femoris (dark green) muscles, (ii) force, and (iii) power output (PO) data received from knee extension ergometer with added trace (iv) demonstrating absolute PO where a positive force (F) was measured. Five contraction cycles at 40 rpm are shown (n=1). **(B)** Dynamic knee extension ergometer. All testing was completed on the dominant leg, with the foot secured in a binding with two buckling straps. The attached crank arm rod turned the flywheel with each contraction to enable passive flexion via the flywheel's generated momentum. Sensors located at the proximal end of the crank arm rod continuously sampled instantaneous force, cadence, and work rate. **(C)** Power-duration relationship. Hyperbolic relationship with two mathematical parameters, the horizontal asymptote (critical power; the boundary between heavy and severe intensity domains) and the curvature constant (W′; the finite capacity to complete work above critical power) shown. **(D)** Quadriceps volume determination and patellar tendon moment arm measurement. Magnetic resonance images of the upper and lower femur were aligned, registered, and blended to obtain a single image covering the entire femur region. Manual segmentation, capturing all four muscles in the quadriceps femoris group, was completed and followed by interpolation in the axial plane. A three-dimensional rendering was used to visualize the total muscle volume. Images in the sagittal plane were used to measure the perpendicular distance between the tibio-femoral contact point (filled circle) and the line of the patellar tendon (solid line), taken as the patellar tendon moment arm (dashed line). **(E)** Quadriceps force calculation schematic. Relevant forces and lengths pictured. Green arrows represent force vectors and red bidirectional arrows represent length measurements. Force

measured at the ankle, lower leg length, and patellar tendon moment arm were used to estimate quadriceps force output.

Figure 2: Relationships between quadriceps mass and single-leg aerobic fitness and power-duration parameters. Individual data plotted for females (purple, n=12) and males (green, n=12) with separate regression lines for each sex. Separate plots are shown for (A) single-leg peak rate of oxygen consumption ($\dot{V}O_2$peak), (B) single-leg peak power output (PPO), (C) critical power (CP), (D) CP torque, (E) CP estimated quadriceps force, and (F) curvature constant (W′). Note that n=11 males for W′ following removal of one outlier.

Figure 3: Estimated marginal means for single-leg aerobic fitness and power-duration parameters after adjusting for quadriceps mass as a covariate. Estimated means shown for variables with no significant interaction between quadriceps mass and sex, evaluated at a mean quadriceps mass of 2.4kg. Separate comparisons are shown for (A) single-leg peak rate of oxygen consumption ($\dot{V}O_2$peak), (B) single-leg peak power output (PPO), (C) critical power (CP), (D) CP torque, and (E) CP quadriceps force. Bars and error bars shown for each sex represent adjusted mean and standard error, respectively. Results of analysis of covariance (ANCOVA) effect of sex after controlling for quadriceps mass shown above each pair of bars.


A
i
1.0
0.5
0.0
-0.5
-1.0
EMG (mV)
ii
150
100
50
0
-50
Force (N)
iii
200
150
100
50
0
-50
PO (W)
iv
200
150
100
50
0
-50
abs PO where F>0 (W)
2
4
6
Time (s)
B
C
Power Output
Severe
W'
Critical Power
Heavy
Duration
D
E


Female
Male
A
$\dot{V}O_2$peak (L·min^{-1})
2000
1500
1000
500
0
$R^2 = 0.291$
$p = 0.070$
$R^2 = 0.114$
$p = 0.283$
Quadriceps Mass (kg)
0
1
2
3
4
5
B
PPO (W)
60
40
20
0
$R^2 = 0.343$
$p = 0.045$
$R^2 = 0.571$
$p = 0.004$
Quadriceps Mass (kg)
C
CP (W)
60
40
20
0
$R^2 = 0.364$
$p = 0.038$
$R^2 = 0.124$
$p = 0.261$
Quadriceps Mass (kg)
D
CP Torque (Nm)
40
30
20
10
0
$R^2 = 0.475$
$p = 0.013$
$R^2 = 0.153$
$p = 0.209$
Quadriceps Mass (kg)
E
CP Quadriceps Force (N)
800
600
400
200
0
$R^2 = 0.415$
$p = 0.024$
$R^2 = 0.150$
$p = 0.213$
Quadriceps Mass (kg)
F
W′ (kJ)
5.0
4.0
3.0
2.0
1.0
0.0
$R^2 = 0.001$
$p = 0.921$
$R^2 = 0.692$
$p = 0.001$
Quadriceps Mass (kg)

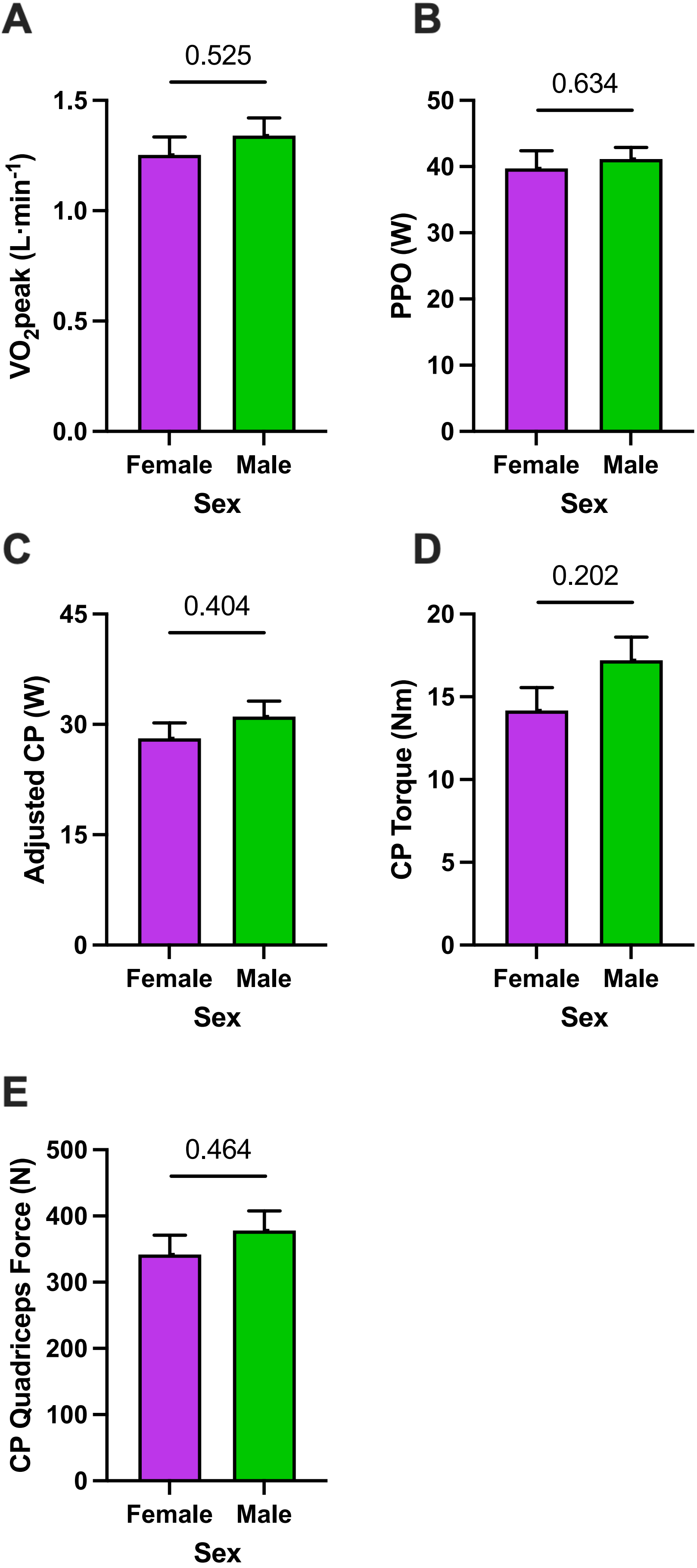

A
0.525
VO₂peak (L·min⁻¹)
1.5
1.0
0.5
0.0
Female
Male
Sex
B
0.634
PPO (W)
50
40
30
20
10
0
Female
Male
Sex
C
0.404
Adjusted CP (W)
45
30
15
0
Female
Male
Sex
D
0.202
CP Torque (Nm)
20
15
10
5
0
Female
Male
Sex
E
0.464
CP Quadriceps Force (N)
500
400
300
200
100
0
Female
Male
Sex

Table 1: Participant Characteristics and Whole-Body Aerobic Fitness.

	Total **(n=24)**	**Males** **(n=12)**	**Females** **(n=12)**	**Sex Difference** **(p)**
Age (years)	28 [6]	27 [6]	29 [6]	0.606
Height (cm)	175 [8]	182 [3]	168 [7]	**<0.001**
Body mass (kg)	73.0 [10.5]	80.1 [8.7]	65.9 [6.8]	**<0.001**
Fat-free mass (kg)	56.7 [10.8]	65.0 [8.4]	48.5 [4.9]	**<0.001**
$\dot{V}O_2$max ($L \cdot min^{-1}$)	3.4 [0.7]	3.8 [0.5]	2.9 [0.4]	**<0.001**
$\dot{V}O_2$max ($mL \cdot kgBM^{-1} \cdot min^{-1}$)	46.0 [7.0]	48.1 [6.2]	43.9 [7.4]	0.145
$\dot{V}O_2$max ($mL \cdot kgFFM^{-1} \cdot min^{-1}$)	59.4 [6.8]	59.5 [7.9]	59.2 [6.0]	0.921
PPO (W)	290 [51]	321 [39]	259 [43]	**0.001**
PPO ($W \cdot kgBM^{-1}$)	4.0 [0.6]	4.0 [0.5]	4.0 [0.7]	0.810
PPO ($W \cdot kgFFM^{-1}$)	5.2 [0.6]	5.0 [0.6]	5.3 [0.6]	0.157
Quadriceps mass (kg)	2.4 [0.6]	2.8 [0.6]	1.9 [0.3]	**<0.001***
PTMA (mm)	43.1 [3.1]	45.6 [1.6]	40.6 [1.9]	**<0.001**

Note. Data are reported as mean and [standard deviation]. p-values are provided for independent samples t tests between males and females. Welch's test was used where variance was not equal between groups (*). Statistically significant differences are indicated with bold text. $\dot{V}O_2$max, maximal rate of oxygen uptake; BM, body mass; FFM, fat-free mass; PPO, peak power output; PTMA, patellar tendon moment arm.

Table 2: Sex Differences in Dynamic Knee Extension Critical Power (CP) Normalized to Quadriceps Mass (QM)

Variable	**Total (n=24)**	**Males (n=12)**	**Females (n=12)**	**Sex Difference (p)**
CP (W)	29.6 [7.4]	33.8 [6.6]	25.4 [5.6]	**0.003**
CP ($W \cdot kgQM^{-1}$)	12.7 [2.4]	12.1 [2.4]	13.3 [2.4]	0.212
CP Torque (Nm)	15.7 [5.4]	19.2 [5.1]	12.2 [2.9]	**<0.001**
CP Torque ($Nm \cdot kgQM^{-1}$)	8.8 [1.5]	8.9 [1.8]	8.7 [1.2]	0.700
CP Force (N)	360.0 [105.5]	420.4 [102.2]	299.6 [70.0]	**0.003**
CP Force ($N \cdot kgQM^{-1}$)	153.5 [32.0]	149.9 [36.3]	157.0 [28.1]	0.600
W′ (kJ)	1.94 [1.04]	2.40 [1.27]	1.47 [0.42]	**0.025**
W′ ($kJ \cdot kgQM^{-1}$) [a]	0.81 [0.33]	0.83 [0.40]	0.79 [0.26]	-

Data are reported as mean and [standard deviation]. p-values are provided for independent samples t tests between males and females. Statistically significant differences are indicated with bold text. Note that n=11 males for W′ following removal of one outlier. CP, critical power; W′, curvature constant; QM, quadriceps mass.

[a] The assumption of homogeneity of slopes was violated and thus normalized comparisons should be interpreted with caution for W′. Accordingly, t test results are not reported.

Table 3: Sex Differences in Critical Power Adjusted for Quadriceps Mass.

	Sex * Quadriceps Mass (F(3,20); p)	**Sex (F(2,21); p)**	**Quadriceps Mass (F(2,21); p)**
CP (W)	1.371; 0.255	0.726; 0.404	4.352; **0.049**
Torque at CP (Nm)	0.651; 0.429	1.737; 0.202	5.521; **0.029**
Quadriceps force at CP (N)	0.882; 0.359	0.555; 0.464	5.287; **0.032**

Note. F-statistics and p-values for ANCOVA models with quadriceps mass as a covariate. Models were first run with an interaction term; if the interaction was not significant, it was removed to assess main effects. Statistically significant effects indicated with bold text. CP, critical power.

Table 4: Variable Association with Power-Duration Relationship Parameters.

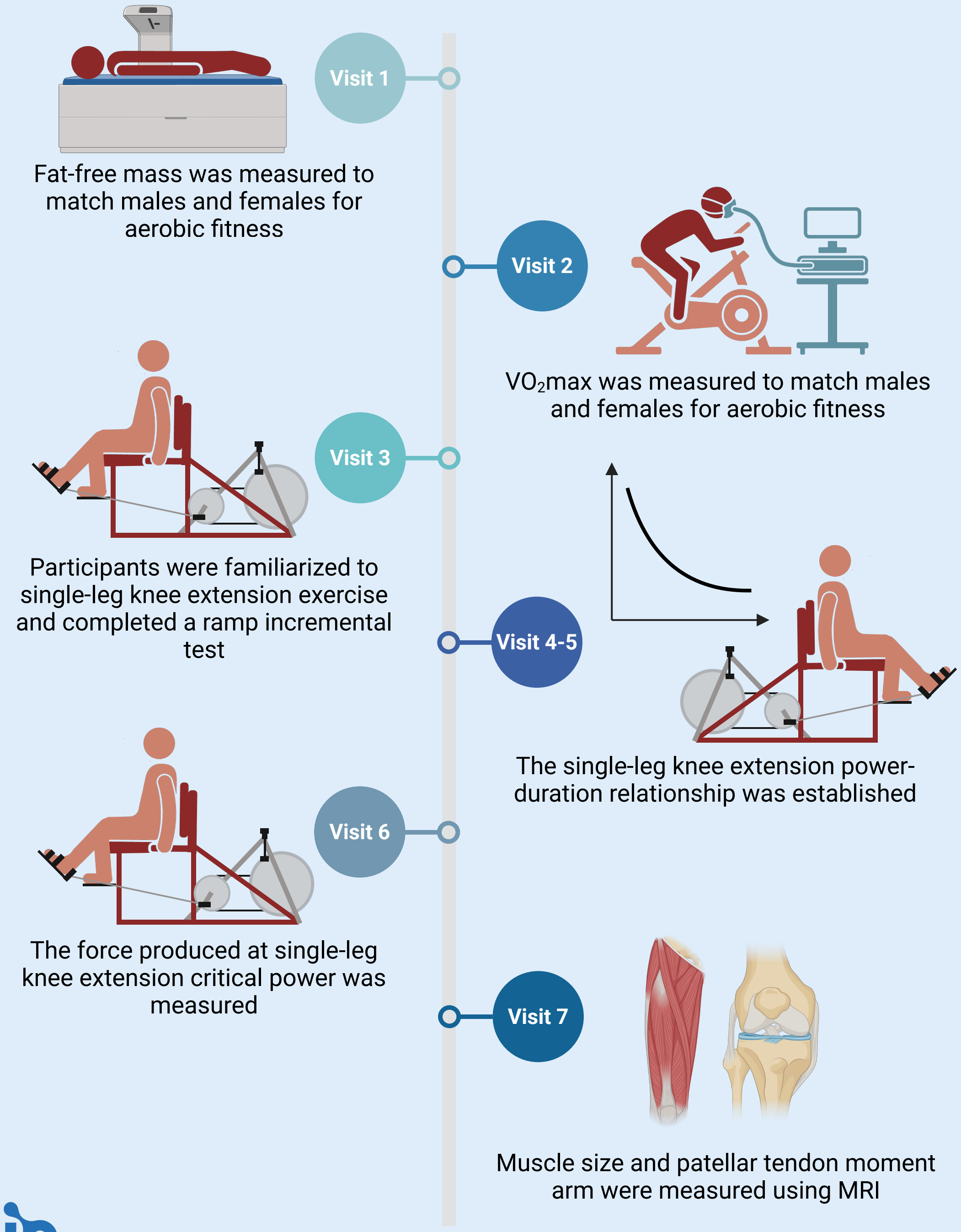
	Bivariate Correlations		**Controlled for Quadriceps Mass (kg)**	
	CP (r; p)	**W′ (r; p)**	**CP (r; p)**	**W′ (r; p)**
PTMA (mm)	0.602; **0.002**	0.363; 0.089	0.271; 0.210	−0.280, 0.207
Whole-body $\dot{V}O_2$max ($L \cdot min^{-1}$)	0.814; **<0.001**	0.384; 0.071	0.635; **0.001**	−0.501; **0.018**
Whole-body PPO (W)	0.855; **<0.001**	0.265; 0.221	0.724; **<0.001**	−0.631; **0.002**
Single-leg $\dot{V}O_2$peak ($L \cdot min^{-1}$)	0.775; **<0.001**	0.226, 0.300	0.625; **0.001**	−0.416; 0.054
Single-leg PPO (W)	0.862; **<0.001**	0.496; **0.016**	0.760; **<0.001**	−0.357; 0.103
MVC torque (Nm)	0.546; **0.006**	0.768; **0.001**	−0.085; 0.699	0.390; 0.073
MVC quadriceps force (N)	0.416; **0.043**	0.745; **0.001**	−0.169; 0.442	0.433; **0.044**

Note. Pearson correlation coefficients (r) and p-values are shown for each bivariate correlation, and for each partial correlation when controlled for quadriceps mass. Statistically significant correlations are indicated with bold text. CP, critical power; W′, curvature constant; PTMA, patellar tendon moment arm; $\dot{V}O_2$max, maximal rate of oxygen consumption; PPO, peak power output; $\dot{V}O_2$peak, peak rate of oxygen consumption; MVC, maximal voluntary contraction.

Sex Differences in the Power-Duration Relationship for Dynamic Knee Extension are Largely Explained by Muscle Size

METHODS

Participants visited the laboratory seven times over ~3 weeks.



Visit 1

Fat-free mass was measured to match males and females for aerobic fitness

Visit 2

VO_2max was measured to match males and females for aerobic fitness

Visit 3

Participants were familiarized to single-leg knee extension exercise and completed a ramp incremental test

Visit 4-5

The single-leg knee extension power-duration relationship was established

Visit 6

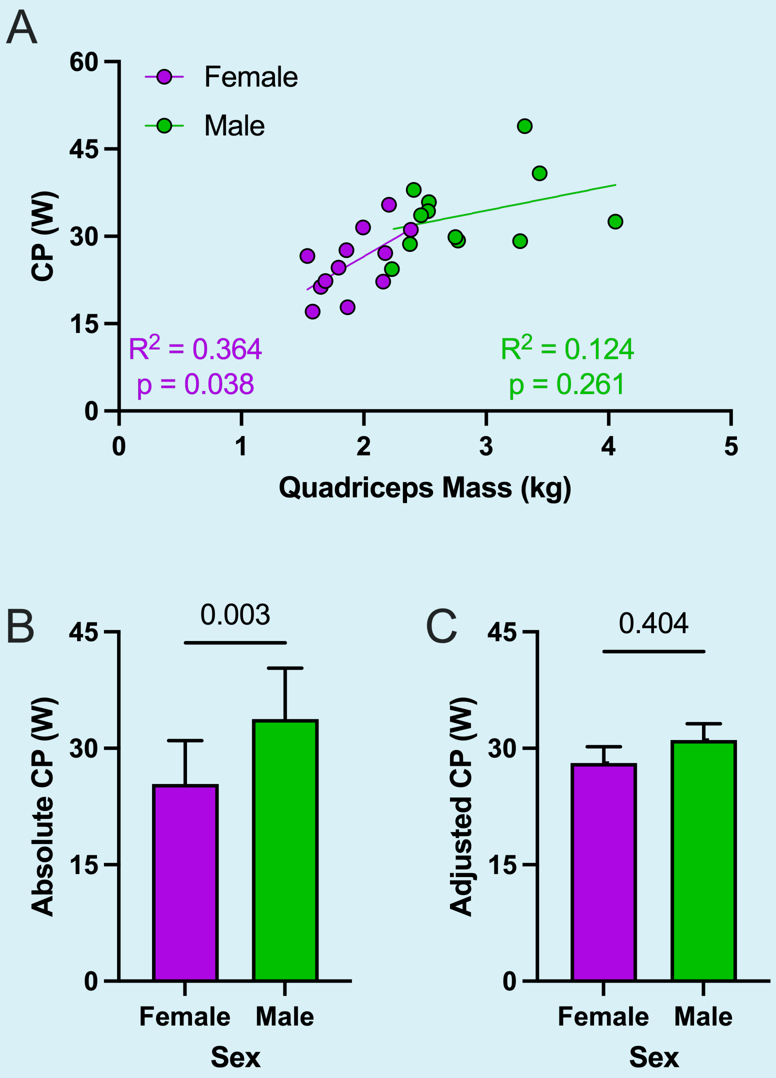
The force produced at single-leg knee extension critical power was measured

Visit 7

Muscle size and patellar tendon moment arm were measured using MRI

OUTCOME

Critical power was positively related to quadriceps mass (A; r=0.659, p<0.001), and was greater in males than females (B; p=0.003); however, when adjusted for quadriceps mass, critical power was not different between sexes (C; p=0.404).



CONCLUSIONS

Sex differences in small muscle mass endurance performance are likely due to muscle size rather than innate differences in muscle endurance capacity between males and females.