Effect of Crank Length on Joint-Specific Power during Maximal Cycling

PAUL R. BARRATT[1,2], THOMAS KORFF[1], STEVE J. ELMER[3], and JAMES C. MARTIN[3]

[1]Centre for Sports Medicine and Human Performance, Brunel University, Uxbridge, UNITED KINGDOM;
[2]Department of Performance Analysis and Biomechanics, English Institute of Sport, Manchester, UNITED KINGDOM;
and [3]Department of Exercise and Sport Science, University of Utah, Salt Lake City, UT

ABSTRACT

BARRATT, P. R., T. KORFF, S. J. ELMER, and J. C. MARTIN. Effect of Crank Length on Joint-Specific Power during Maximal Cycling. *Med. Sci. Sports Exerc.*, Vol. 43, No. 9, pp. 1689–1697, 2011. Previous investigators have suggested that crank length has little effect on overall short-term maximal cycling power once the effects of pedal speed and pedaling rate are accounted for. Although overall maximal power may be unaffected by crank length, it is possible that similar overall power might be produced with different combinations of joint-specific powers. Knowing the effects of crank length on joint-specific power production during maximal cycling may have practical implications with respect to avoiding or delaying fatigue during high-intensity exercise. **Purpose**: The purpose of this study was to determine the effect of changes in crank length on joint-specific powers during short-term maximal cycling. **Methods**: Fifteen trained cyclists performed maximal isokinetic cycling trials using crank lengths of 150, 165, 170, 175, and 190 mm. At each crank length, participants performed maximal trials at pedaling rates optimized for maximum power and at a constant pedaling rate of 120 rpm. Using pedal forces and limb kinematics, joint-specific powers were calculated via inverse dynamics and normalized to overall pedal power. **Results**: ANOVAs revealed that crank length had no significant effect on relative joint-specific powers at the hip, knee, or ankle joints ($P > 0.05$) when pedaling rate was optimized. When pedaling rate was constant, crank length had a small but significant effect on hip and knee joint power (150 vs 190 mm only) ($P < 0.05$). **Conclusions**: These data demonstrate that crank length does not affect relative joint-specific power once the effects of pedaling rate and pedal speed are accounted for. Our results thereby substantiate previous findings that crank length *per se* is not an important determinant of maximum cycling power production. **Key Words:** BIOMECHANICS, MUSCLE POWER, SPRINT CYCLING, CYCLING PERFORMANCE

Muscular power produced during cyclic contractions is primarily limited by muscle shortening velocity, excitation, and length excursion (11,13, 15,23). These constraints have been reported to affect muscular power during voluntary activities (1,12) and *in situ* and *in vitro* isolated muscle actions (3,11,24). In particular, these constraints limit power production during maximal voluntary cycling exercise (6,15,27–29). During cycling, muscle shortening velocities and hence velocity-specific forces are generally constrained by pedal speed (28,29), which is the product of crank length and angular velocity. Further, muscle excitations across the complete pedal cycle are governed by pedaling rate (15). Finally, crank length may also directly affect muscular force production via the length–tension relationship (28,29). Thus, crank length may affect short-term maximal cycling power, which is considered to be a major determinant of sprint cycling performance (16), via several basic aspects of neuromuscular function.

Investigators have previously reported differing results with respect to the effect of crank length on short-term maximal cycling power (10,15,19,26,28,29). Inbar et al. (10) and Too and Landwer (26) used a Wingate anaerobic test model and reported that peak cycling power varied by 8% over crank lengths of 110–230 mm. The Wingate test used by these investigators is limited in that it does not account for changes in pedaling rate, which strongly affects short-term maximal cycling power (7,22). Consequently, it is not clear whether these results reflect the effect of crank length *per se* or of pedaling rate on maximum cycling power. Yoshihuku and Herzog (28,29) used a mathematical model of the lower limb during cycling to investigate the effect of crank length on crank power. These authors reported that maximum power varied by 0%–10% for crank lengths of 130–210 mm. Their model included an assumption of instantaneous muscle excitation and relaxation and thus was not affected by excitation/relaxation kinetics, which are known to affect maximum muscular power production (3,27). Martin and Spirduso (19) and Martin et al. (15) reported short-term maximal cycling power across a range of pedaling rates and crank lengths (120–220 mm). These authors reported that the effect of crank length on maximum

Address for correspondence: Thomas Korff, Ph.D., Centre for Sports Medicine and Human Performance, Brunel University, Uxbridge UB8 3PH, United Kingdom; E-mail: thomas.korff@brunel.ac.uk.
Submitted for publication June 2010.
Accepted for publication January 2011.

0195-9131/11/4309-1689/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0b013e3182125e96

power production was small (<4%) and only significant when comparing extreme lengths (120 and 220 mm). They also reported that the product of pedaling rate and pedal speed (a construct variable they termed “cyclic velocity” (Hz·ms^{-1})) accounted for most of the variation in cycling power across all the crank lengths tested. These findings suggest that, once pedaling rate and pedal speed are accounted for, crank length has only a small effect on short-term maximal cycling power.

Cycling power is produced mainly by the muscles that span the hip, knee, and ankle joints (2,14). These joint-specific powers can be determined with standard inverse dynamics techniques and provide insight into movement strategies that are not apparent when observing overall cycling power. Martin and Brown (14) demonstrated that short-term maximal cycling power is produced mainly through hip extension, knee extension and flexion, and ankle extension (plantarflexion) actions. They further demonstrated that during a maximal 30-s cycling trial, hip extension power was the most resistant to fatigue, whereas knee extension power was highly fatigable. In addition, fatigue has been reported to be reduced when cycling with greater crank lengths (25). Tomas et al. (25) speculated that increased crank length may have caused a shift in the relative power produced at the hip, knee, and ankle such that the longer cranks relied more on the fatigue-resistant hip extension power. Taken together, these findings make it clear that a greater understanding of the effects of crank length on joint-specific power production during short-term maximal cycling may have important implications for cycling performance.

The purpose for conducting this study was to determine whether changes in crank length affect the relative contributions of hip, knee, and ankle powers to overall cycling power. We investigated five crank lengths within the range previously reported (145–195 mm (19)) to allow similar overall cycling power. These crank lengths were used with pedaling rate controlled in two ways. First, all crank lengths were tested at a standard pedaling rate of 120 rpm that is associated with the apex of the power–pedaling rate curve for standard crank lengths (27). Second, each crank length was evaluated at separate pedaling rates set to produce maximum short-term power for each length (19). On the basis of previous results (19,27), we hypothesized that the effect of crank length on joint-specific power would depend on how pedaling rate is accounted for. More specifically, we hypothesized that a) crank length would not affect relative joint-specific power when pedaling rate is optimized for maximum power and b) crank length would affect relative joint-specific power when pedaling rate is constant.

METHODS

Fifteen cyclists (12 males (76 ± 7 kg) and 3 females (66 ± 7 kg)) age 19–44 yr volunteered for the study. All participants were experienced cyclists who regularly took part in local cycling races. The procedures were explained verbally and in writing, and all participants provided written informed consent. The procedures used in this study were reviewed and approved by the Research Ethics Committee of Brunel University and the Institutional Review Board of the University of Utah.

All participants reported to the Neuromuscular Function Laboratory at the University of Utah on four separate occasions. During the week before experimental data collection, participants performed two familiarization sessions with the shortest and longest crank lengths (150 and 190 mm). Participants did not perform familiarization sessions with the standard crank lengths (165, 170, and 175 mm) because they regularly cycled with cranks within this range. During each familiarization session, participants performed 10 min of submaximal cycling at a self-selected power output of 100–240 W followed by two maximal cycling trials of 3 s. These trials were performed with the 150- and 190-mm crank lengths during each visit. The order of presentation of the two lengths was counterbalanced between participants and visits. The familiarization sessions allowed the participants to practice twice with the shortest and longest crank lengths before experimental data collection. This procedure is in accordance with our previous investigations (17).

Experimental data were collected on two separate days and began at the same time of day for each participant. On each experimental day, participants reported to the laboratory where body mass, thigh length (greater trochanter to lateral femoral condyle), leg length (lateral femoral condyle to lateral malleolus), foot length (heel to toe), and kinematic foot length (pedal spindle to lateral malleolus) were recorded. All anthropometric measures were collected by the same investigator. Ergometer seat height was set to participants’ preferred seat height as measured on their own personal training bicycles. When crank length was changed, the seat height was adjusted to ensure a constant distance between the top of the saddle and the pedal spindle when the leg was in its most extended position. Handlebar height was adjusted so that the vertical distance between the saddle and the handlebar was constant for all crank length conditions. Participants wore cycling shoes with cleats that locked onto the pedal interface (Speedplay, Inc., San Diego, CA). Participants performed a 5-min warm-up of submaximal cycling at a self-selected power output of 100–240 W with the crank length to be tested first and rested for 2 min before performing two 3-s maximal isokinetic cycling trials. Participants performed one trial at a pedaling rate resulting in a cyclic velocity of 4.27 Hz·ms^{-1} (15) and one trial at a pedaling rate of 120 rpm. The pedaling rates corresponding to each crank length can be found in Table 1. The condition of pedaling rate matched for cyclic velocity was intended to elicit maximum power (the apex of the power–pedaling rate curve) for each crank length (19). Maximum power was defined as pedal power averaged over all full revolutions within the 3 s cycling trial. The condition of constant pedaling rate at 120 rpm was included because this value is

TABLE 1. Power delivered to the right pedal during maximal cycling with variations in crank length and pedaling rate.

	Constant Pedaling Rate						**Optimized Pedaling Rate**				
Crank length (mm)	150	165	170	175	190		150	165	170	175	190
Pedal rate (rpm)	120	120	120	120	120		128	122	120	118	114
Pedal power (W)	494 ± 113	497 ± 109	504 ± 116	505 ± 114	495 ± 109		495 ± 115	499 ± 114	504 ± 116	504 ± 110	492 ± 104
Ankle power (%)											
	150	**165**	**170**	**175**	**190**		**150**	**165**	**170**	**175**	**190**
150	**12 ± 8**	0.00	−0.03	−0.06	−0.04	**150**	**10 ± 9**	−0.25	−0.23	−0.35	−0.28
165	0.00	**12 ± 8**	−0.03	−0.07	−0.04	**165**	0.25	**12 ± 8**	0.02	−0.08	−0.02
170	0.03	0.03	**12 ± 8**	−0.03	−0.01	**170**	0.23	−0.02	**12 ± 8**	−0.11	−0.05
175	0.06	0.07	0.03	**12 ± 8**	0.03	**175**	0.35	0.08	0.11	**13 ± 6**	0.06
190	0.04	0.04	0.01	−0.03	**12 ± 7**	**190**	0.28	0.02	0.05	−0.06	**12 ± 7**
Knee power (%)											
	150	**165**	**170**	**175**	**190**		**150**	**165**	**170**	**175**	**190**
150	**45 ± 5**	0.48	0.44	0.43	0.89	**150**	**43 ± 10**	0.13	0.13	0.24	0.30
165	−0.48	**42 ± 6**	−0.02	−0.08	0.41	**165**	−0.13	**42 ± 7**	0.00	0.13	0.21
170	−0.44	0.02	**42 ± 7**	−0.05	0.42	**170**	−0.13	0.00	**42 ± 7**	0.12	0.21
175	−0.43	0.08	0.05	**42 ± 5**	0.51	**175**	−0.24	−0.13	−0.12	**41 ± 5**	0.10
190	−0.89	−0.41	−0.42	−0.51	**39 ± 7**	**190**	−0.30	−0.21	−0.21	−0.10	**41 ± 6**
Hip power (%)											
	150	**165**	**170**	**175**	**190**		**150**	**165**	**170**	**175**	**190**
150	**36 ± 8**	−0.46	−0.36	−0.35	−0.85	**150**	**40 ± 15**	0.04	0.05	0.00	−0.12
165	0.46	**40 ± 8**	0.13	0.17	−0.37	**165**	−0.04	**39 ± 8**	0.02	−0.05	−0.24
170	0.36	−0.13	**39 ± 7**	0.03	−0.54	**170**	−0.05	−0.02	**39 ± 7**	−0.09	−0.28
175	0.35	−0.17	−0.03	**39 ± 6**	−0.61	**175**	0.00	0.05	0.09	**40 ± 7**	−0.21
190	0.85	0.37	0.54	0.61	**43 ± 7**	**190**	0.12	0.24	0.28	0.21	**41 ± 7**
Hip transfer power (%)											
	150	**165**	**170**	**175**	**190**		**150**	**165**	**170**	**175**	**190**
150	**7 ± 2**	0.45	0.16	0.26	0.58	**150**	**7 ± 3**	0.19	0.08	0.29	0.38
165	−0.45	**6 ± 2**	−0.23	−0.11	0.18	**165**	−0.19	**6 ± 3**	−0.12	0.11	0.23
170	−0.16	0.23	**7 ± 3**	0.10	0.37	**170**	−0.08	0.12	**7 ± 3**	0.22	0.33
175	−0.26	0.11	−0.10	**6 ± 3**	0.25	**175**	−0.29	−0.11	−0.22	**6 ± 3**	0.13
190	−0.58	−0.18	−0.37	−0.25	**6 ± 3**	**190**	−0.38	−0.23	−0.33	−0.13	**6 ± 3**

Joint-specific powers are averaged over complete pedal cycles and normalized to pedal power. Joint-specific powers are presented as means ± SD on the main diagonal of each table. Effect sizes for pairwise comparisons are presented in the remaining cells. Values in bold indicate statistical significance.

typically associated with the apex of the power–pedaling rate curve for standard crank lengths (27). Each participant performed a total of nine maximal cycling trials (two pedaling rate conditions and five crank lengths—the trial at 120 rpm and a crank length of 170 mm was used for both pedaling rate conditions). The order of crank lengths was randomized. Within each crank length condition, the order of the two maximal trials was also randomized. The nine maximal cycling trials were performed during two testing days. Participants were either tested on two crank lengths on the first day and three crank lengths on the second day of data collection or vice versa. For all maximal cycling trials, participants were instructed to use the absolute maximum effort they could produce while remaining seated. Standardized verbal encouragement was provided throughout the trial.

A Monark (Vansbro, Sweden) cycle ergometer frame and flywheel were used to construct an isokinetic ergometer. The ergometer flywheel was driven by a 3750-W direct-current motor (model CDP3605; Baldor Electric Company, Fort Smith, AR). The motor was controlled by a speed controller equipped with regenerative braking (model RG5500U; Minarik, Glendale, CA). The ergometer controlled the pedaling rate to within an accuracy of 1 rpm for each experimental trial. An adjustable crank (SRM multilength crank; Schoberer Rad Messtechnik, Jülich, Germany) was used to provide crank lengths of 150, 165, 170, 175, or 190 mm. The right pedal was equipped with two three-component piezoelectric force transducers (Kistler 9251; Kistler USA, Amherst, NY), and the right pedal and crank were equipped with digital position encoders (S5S-1024-IB; US Digital, Vancouver, WA), which measured the angles of the pedal and the crank in the inertial reference frame. Using the pedal angle, normal and tangential pedal forces were resolved into (absolute) vertical and horizontal components. The position of the right iliac crest was recorded using a two-segment instrumented spatial linkage as described by Martin et al. (18). Pedal forces and pedal, crank, and instrumented spatial linkage positions were recorded at 240 Hz using Bioware software (Kistler USA). These data were filtered using a fourth-order zero-lag Butterworth low-pass filter with a cutoff frequency of 8 Hz.

The position of the hip joint was inferred from the position of the iliac crest, assuming a constant offset that was measured in a static condition (20). The location of the ankle joint was determined using the angular positions of the crank and pedal and the length from the pedal spindle to the lateral malleolus. It was assumed that the position of the lateral malleolus relative to the pedal surface was fixed throughout the pedal cycle (9). Using the locations of the hip and ankle joints and thigh and leg lengths, the position of the knee joint center was determined by the law of cosines. Segment angles were calculated from joint positions and segment lengths, and relative joint angles were calculated from segment angles. Linear and angular velocities and accelerations of the limb segments were determined by finite differentiation of position data with respect to time.

Segmental masses, moments of inertia, and the segmental center of mass locations were estimated using the regression equations reported by de Leva (5). Sagittal plane joint reaction forces and net joint moments at the hip, knee, and ankle were derived using standard inverse dynamics techniques (8). To perform the inverse dynamics analysis, we assumed that the hip, knee, and ankle functioned as frictionless revolute joints and that the foot, leg, and thigh were rigid segments with fixed centers of mass and segmental moments of inertia. Joint-specific powers were calculated as the product of net joint moments and joint angular velocities; power transferred across the hip joint was calculated as the dot product of hip joint reaction force and linear velocity (2). Pedal power was defined as the dot product of pedal force and linear velocity.

Data representative of all complete pedal cycles during the trial were analyzed. Each trial lasted 3 s and therefore included four to six complete pedal cycles, depending on the pedaling rate. Pedal and joint-specific powers were calculated as average values over these pedal cycles. Joint-specific powers were normalized to average pedal power. In addition, we calculated averaged extension and flexion powers at each joint. Extension and flexion phases were defined on the basis of the numerical sign of the corresponding joint angular velocity (positive and negative joint angular velocities corresponding to extension and flexion, respectively). Extension and flexion powers were normalized to average pedal power. Because joint-specific powers are affected by joint angular velocity and excursion (28), we additionally quantified the effect of crank length on angular velocities and excursions at the ankle, knee, and hip for the two pedaling rate conditions. Joint angular velocities were averaged over the corresponding extension and flexion phases. Joint excursion was defined as the difference between the maximum and minimum joint angles for the corresponding joint.

To test the hypothesis that the effect of crank length on joint-specific power would depend on how pedaling rate is accounted for, we performed a multivariate ANOVA (repeated-measures factor MANOVA) with 10 dependent variables (hip, hip transfer, knee, ankle, hip extension, hip flexion, knee extension, knee flexion, ankle extension, and

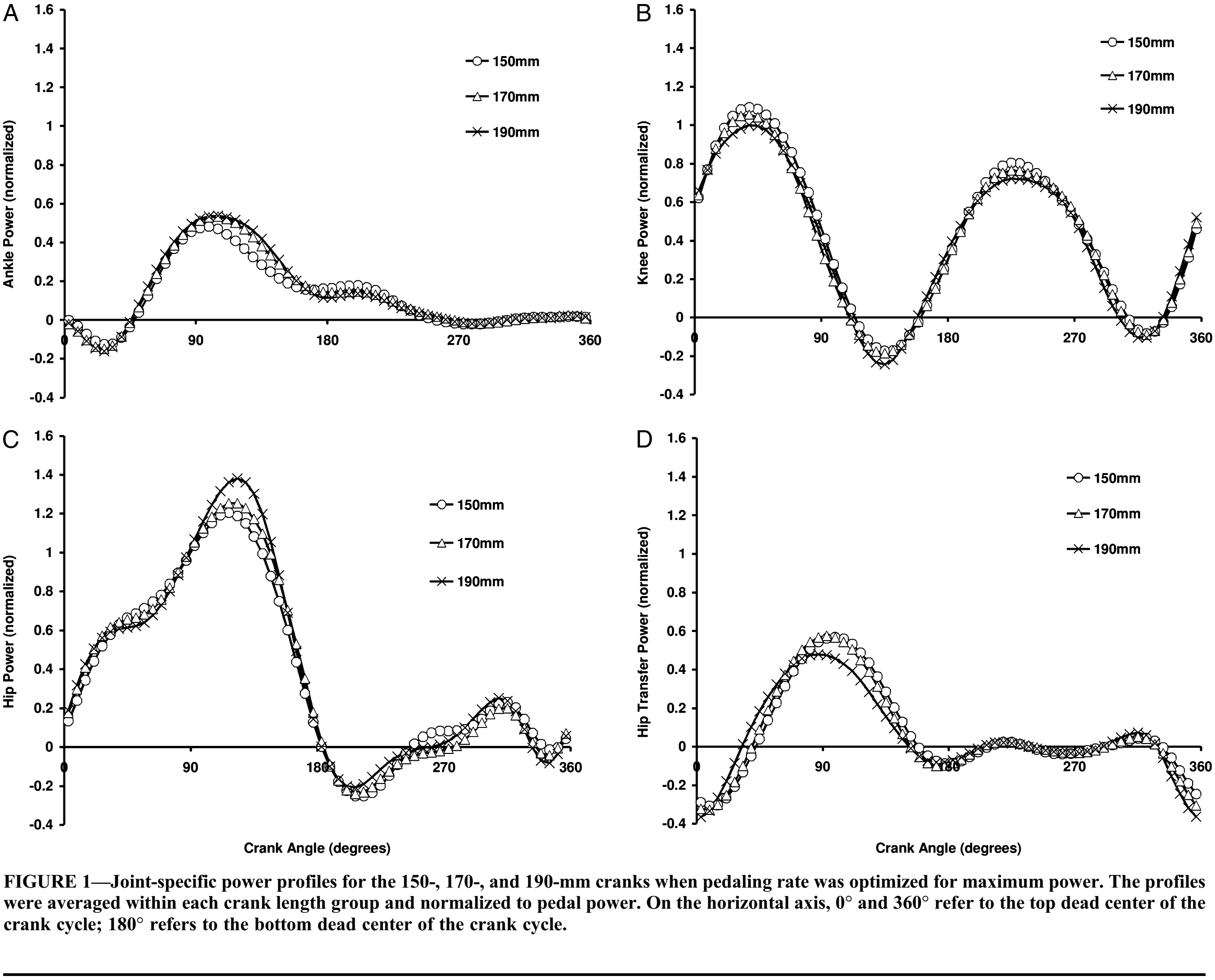

FIGURE 1—Joint-specific power profiles for the 150-, 170-, and 190-mm cranks when pedaling rate was optimized for maximum power. The profiles were averaged within each crank length group and normalized to pedal power. On the horizontal axis, 0° and 360° refer to the top dead center of the crank cycle; 180° refers to the bottom dead center of the crank cycle.

ankle flexion powers), with crank length and method of accounting for pedaling rate (constant pedaling rate vs optimized for maximum power) being the within-subject factors. If the crank × method interaction was significant, we then performed separate follow-up repeated-measures MANOVAs for each method of standardizing pedaling rate. The significance level for all MANOVAs was set to $P < 0.05$. If these follow-up MANOVA were significant, we performed one-way ANOVAs with repeated measures for each dependent variable, with crank length being the within-subject factor. To account for type I error inflation, we adjusted the significance level of these ANOVAs by dividing the original significance level of $P < 0.05$ by the number of dependent variables. If an ANOVA indicated a significant main effect for crank length, *post hoc* pairwise comparisons (Bonferroni) were performed to identify crank length pairs with significantly different relative joint-specific powers. All statistical procedures were performed using SPSS 14.0 (SPSS, Inc., Chicago, IL). To further describe the interactive effect of crank and method to account for pedaling rate on joint-specific power, means, SD, and effect sizes (Cohen's d) were calculated for pairwise comparisons. The same descriptive statistics were used to report the effect of crank length on joint angular velocities and excursions. Effect sizes were interpreted on the basis of Cohen's (4) classification scheme effect sizes <0.5 were considered to be small, effect sizes between 0.5 and 0.8 were considered to be moderate, and effect sizes >0.8 were considered to be large.

RESULTS

The repeated-measures factor MANOVA revealed that the crank length by method of accounting for pedaling rate was significant (Wilks' $\lambda = 0.284$, $F_{36,182} = 2.201$, $P = 0.002$).

TABLE 2. Extension and flexion powers produced at the ankle, knee, and hip.

	Constant Pedaling Rate						Optimized Pedaling Rate				
	Ankle Extension Power (%)						Ankle Extension Power (%)				
	150	165	170	175	190		150	165	170	175	190
150	**29 ± 10**	0.12	0.14	0.19	0.32	**150**	**24 ± 12**	−0.24	−0.29	−0.35	−0.25
165	−0.12	**27 ± 10**	0.01	0.06	0.20	**165**	0.24	**27 ± 11**	−0.04	−0.10	−0.01
170	−0.14	−0.01	**27 ± 10**	0.05	0.19	**170**	0.29	0.04	**27 ± 10**	−0.06	0.03
175	−0.19	−0.06	−0.05	**27 ± 10**	0.13	**175**	0.35	0.10	0.06	**28 ± 9**	0.09
190	−0.32	−0.20	−0.19	−0.13	**25 ± 10**	**190**	0.25	0.01	−0.03	−0.09	**27 ± 11**
	Ankle Flexion Power (%)						Ankle Flexion Power (%)				
	150	165	170	175	190		150	165	170	175	190
150	**−8 ± 6**	0.00	−0.13	−0.33	−0.32	**150**	**−7 ± 6**	−0.05	0.03	−0.18	−0.05
165	0.00	**−8 ± 7**	−0.13	−0.32	−0.31	**165**	0.05	**−7 ± 5**	0.08	−0.13	0.01
170	0.13	0.13	**−7 ± 6**	−0.21	−0.20	**170**	−0.03	−0.08	**−7 ± 6**	−0.22	−0.08
175	0.33	0.32	0.21	**−6 ± 5**	0.00	**175**	0.18	0.13	0.22	**−6 ± 4**	0.15
190	0.32	0.31	0.20	0.00	**−6 ± 5**	**190**	0.05	−0.01	0.08	−0.15	**−7 ± 5**
	Knee Extension Power (%)						Knee Extension Power (%)				
	150	165	170	175	190		150	165	170	175	190
150	**47 ± 14**	0.27	0.19	0.11	0.33	**150**	**46 ± 18**	0.07	0.12	0.18	0.20
165	−0.27	**43 ± 15**	−0.08	−0.17	0.06	**165**	−0.07	**45 ± 15**	0.06	0.13	0.14
170	−0.19	0.08	**44 ± 16**	−0.09	0.13	**170**	−0.12	−0.06	**44 ± 16**	0.06	0.07
175	−0.11	0.17	0.09	**45 ± 14**	0.23	**175**	−0.18	−0.13	−0.06	**43 ± 13**	0.02
190	−0.33	−0.06	−0.13	−0.23	**42 ± 15**	**190**	−0.20	−0.14	−0.07	−0.02	**43 ± 13**
	Knee Flexion Power (%)						Knee Flexion Power (%)				
	150	165	170	175	190		150	165	170	175	190
150	**43 ± 11**	0.14	0.24	0.32	0.65	**150**	**40 ± 13**	0.08	0.01	0.05	0.16
165	−0.14	**41 ± 11**	0.10	0.18	0.50	**165**	−0.08	**39 ± 10**	−0.08	−0.04	0.09
170	−0.24	−0.10	**40 ± 11**	0.08	0.38	**170**	−0.01	0.08	**40 ± 11**	0.04	0.17
175	−0.32	−0.18	−0.08	**40 ± 10**	0.32	**175**	−0.05	0.04	−0.04	**40 ± 9**	0.14
190	−0.65	−0.50	−0.38	−0.32	**37 ± 8**	**190**	−0.16	−0.09	−0.17	−0.14	**39 ± 10**
	Hip Extension Power (%)						Hip Extension Power (%)				
	150	165	170	175	190		150	165	170	175	190
150	**73 ± 20**	−0.31	−0.28	−0.21	−0.58	**150**	**77 ± 24**	−0.04	−0.04	−0.06	−0.19
165	0.31	**79 ± 18**	0.05	0.15	−0.26	**165**	0.04	**78 ± 16**	0.00	−0.03	−0.20
170	0.28	−0.05	**78 ± 16**	0.10	−0.33	**170**	0.04	0.00	**78 ± 16**	−0.02	−0.19
175	0.21	−0.15	−0.10	**76 ± 14**	−0.46	**175**	0.06	0.03	0.02	**78 ± 12**	−0.19
190	0.58	0.26	0.33	0.46	**83 ± 16**	**190**	0.19	0.20	0.19	0.19	**81 ± 15**
	Hip Flexion Power (%)						Hip Flexion Power (%)				
	150	165	170	175	190		150	165	170	175	190
150	**−3 ± 9**	−0.08	0.10	−0.07	−0.17	**150**	**0 ± 16**	0.20	0.26	0.16	0.08
165	0.08	**−2 ± 13**	0.15	0.02	−0.07	**165**	−0.20	**−3 ± 14**	0.06	−0.06	−0.14
170	−0.10	−0.15	**−4 ± 14**	−0.15	−0.23	**170**	−0.26	−0.06	**−4 ± 14**	−0.13	−0.21
175	0.07	−0.02	0.15	**−2 ± 11**	−0.10	**175**	−0.16	0.06	0.13	**−2 ± 11**	−0.10
190	0.17	0.07	0.23	0.10	**−1 ± 12**	**190**	−0.08	0.14	0.21	0.10	**−1 ± 13**

Powers are normalized to pedal power. Means ± SD are presented on the main diagonal of each table. Effect sizes for pairwise comparisons are presented in the remaining cells. Values in bold indicate statistical significance.

The first follow-up repeated-measures MANOVA revealed that crank length did not affect joint powers when pedaling rate was optimized for maximum power (Wilks' $\lambda = 0.490$, $F_{40,180} = 0.932$, $P = 0.591$). Figure 1 illustrates the similarity of relative joint-specific power profiles produced with the 150-, 170-, and 190-mm cranks when pedaling rate was optimized for maximum power.

The second follow-up repeated-measures MANOVA revealed that crank length had a significant effect on joint powers when pedaling rate was constant at 120 rpm (Wilks' $\lambda = 0.224$, $F_{40,180} = 2.179$, $P < 0.001$). Follow-up ANOVAs revealed that crank length significantly affected relative knee and hip powers averaged over complete pedal cycles ($P < 0.001$) (Table 1). *Post hoc t*-tests revealed that cycling with the 150-mm cranks resulted in greater relative knee power ($P = 0.001$) and smaller relative hip power ($P < 0.001$) when compared with the 190-mm cranks. Further, crank length significantly affected relative knee flexion power ($P = 0.011$) and relative hip extension power ($P = 0.044$) (Table 2). *Post hoc t*-tests revealed that relative knee flexion power was greater ($P < 0.001$) and relative hip extension power was smaller ($P = 0.01$) when cycling with 150-mm cranks compared with 190-mm cranks. Figure 2 illustrates that knee and hip power profiles produced with 150 and 190 mm diverge during parts of the crank cycle.

Our analysis of joint angular velocities indicated that when pedaling rate was optimized for maximum power, crank length only had a small effect on joint angular velocities. The corresponding effect sizes were <0.5 (Table 3). When pedaling rate was constant at 120 rpm, longer crank lengths produced greater extension and flexion velocities at the hip and knee than shorter cranks. The effect sizes revealed that this difference increased with more extreme crank length comparisons (Table 3). In particular, effect sizes were large for extension and flexion velocities at the knee and hip joints when the 150-mm cranks were compared with the 190-mm cranks. Our analysis of joint excursions indicated that longer crank lengths resulted in increased hip and knee excursions than shorter cranks during both pedaling rate conditions (Table 4). Again, the effect sizes became larger when more extreme cranks were compared. These differences were similar across both methods of standardizing

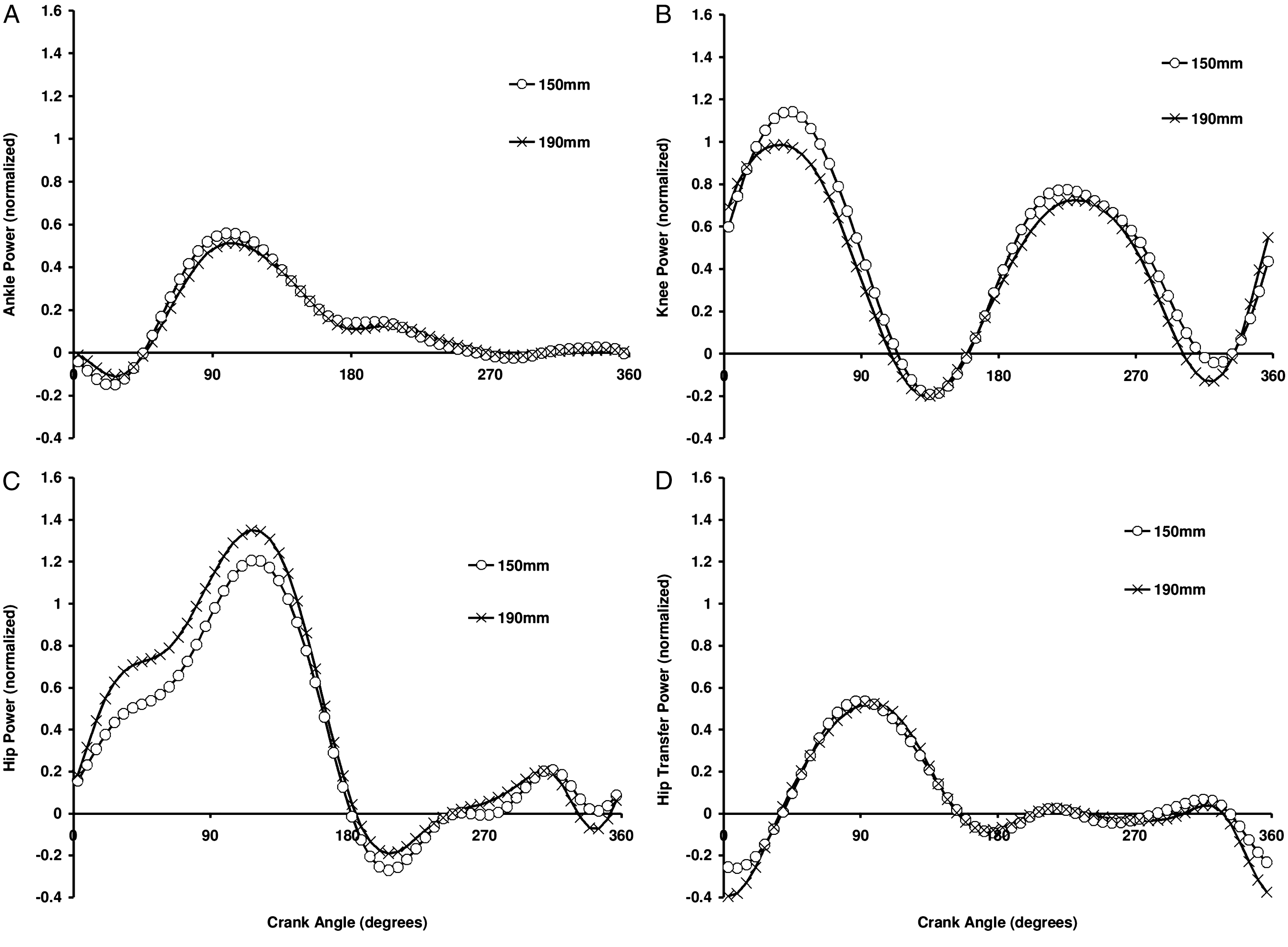

FIGURE 2—Joint-specific power profiles from the 150- and 190-mm cranks when pedaling rate was constant. The profiles were averaged within each crank length group and normalized to pedal power. On the abscissa 0° and 360° refer to the top dead center of the crank cycle; 180° refers to the bottom dead center of the crank cycle.

TABLE 3. Joint angular velocities at the hip, knee, and ankle.

	Constant Pedaling Rate						Optimized Pedaling Rate				
	Ankle Extension Velocity (°·s^{-1})						**Ankle Extension Velocity (°·s^{-1})**				
	150	**165**	**170**	**175**	**190**		**150**	**165**	**170**	**175**	**190**
150	**−136** ± **45**	0.03	−0.04	−0.10	−0.20	**150**	**−128** ± **40**	0.17	0.14	0.06	0.10
165	−0.03	**−137** ± **51**	−0.07	−0.13	−0.22	**165**	−0.17	**−136** ± **50**	−0.04	−0.12	−0.09
170	0.04	0.07	**−134** ± **44**	−0.06	−0.17	**170**	−0.14	0.04	**−134** ± **44**	−0.09	−0.05
175	0.10	0.13	0.06	**−132** ± **40**	−0.11	**175**	−0.06	0.12	0.09	**−131** ± **36**	0.04
190	0.20	0.22	0.17	0.11	**−127** ± **40**	**190**	−0.10	0.09	0.05	−0.04	**−132** ± **38**
	Ankle Flexion Velocity (°·s^{-1})						**Ankle Flexion Velocity (°·s^{-1})**				
	150	**165**	**170**	**175**	**190**		**150**	**165**	**170**	**175**	**190**
150	**155** ± **37**	−0.27	−0.22	−0.12	−0.35	**150**	**147** ± **40**	−0.46	−0.41	−0.28	−0.57
165	0.27	**165** ± **38**	0.04	0.14	−0.08	**165**	0.46	**165** ± **35**	0.03	0.19	−0.12
170	0.22	−0.04	**164** ± **40**	0.10	−0.12	**170**	0.41	−0.03	**164** ± **40**	0.15	−0.14
175	0.12	−0.14	−0.10	**160** ± **39**	−0.22	**175**	0.28	−0.19	−0.15	**158** ± **36**	−0.31
190	0.35	0.08	0.12	0.22	**168** ± **39**	**190**	0.57	0.12	0.14	0.31	**169** ± **36**
	Knee Extension Velocity (°·s^{-1})						**Knee Extension Velocity (°·s^{-1})**				
	150	**165**	**170**	**175**	**190**		**150**	**165**	**170**	**175**	**190**
150	**260** ± **32**	−0.38	−0.54	−0.72	−1.20	**150**	**274** ± **29**	−0.04	−0.07	−0.09	−0.25
165	0.38	**273** ± **33**	−0.12	−0.28	−0.77	**165**	0.04	**275** ± **27**	−0.03	−0.06	−0.22
170	0.54	0.12	**276** ± **26**	−0.18	−0.74	**170**	0.07	0.03	**276** ± **26**	−0.03	−0.19
175	0.72	0.28	0.18	**281** ± **24**	−0.60	**175**	0.09	0.06	0.03	**277** ± **27**	−0.16
190	1.20	0.77	0.74	0.60	**296** ± **26**	**190**	0.25	0.22	0.19	0.16	**281** ± **25**
	Knee Flexion Velocity (°·s^{-1})						**Knee Flexion Velocity (°·s^{-1})**				
	150	**165**	**170**	**175**	**190**		**150**	**165**	**170**	**175**	**190**
150	**−278** ± **39**	0.55	0.48	0.81	1.00	**150**	**−293** ± **39**	0.15	0.09	0.23	0.24
165	−0.55	**−300** ± **39**	−0.08	0.20	0.42	**165**	−0.15	**−298** ± **33**	−0.06	0.08	0.10
170	−0.48	0.08	**−296** ± **37**	0.30	0.52	**170**	−0.09	0.06	**−296** ± **37**	0.14	0.15
175	−0.81	−0.20	−0.30	**−307** ± **31**	0.26	**175**	−0.23	−0.08	−0.14	**−301** ± **33**	0.01
190	−1.00	−0.42	−0.52	−0.26	**−315** ± **35**	**190**	−0.24	−0.10	−0.15	−0.01	**−302** ± **33**
	Hip Extension Velocity (°·s^{-1})						**Hip Extension Velocity (°·s^{-1})**				
	150	**165**	**170**	**175**	**190**		**150**	**165**	**170**	**175**	**190**
150	**−169** ± **36**	0.41	0.41	0.52	0.90	**150**	**−180** ± **33**	0.18	0.06	0.07	0.28
165	−0.41	**−183** ± **35**	−0.03	0.08	0.48	**165**	−0.18	**−186** ± **30**	−0.13	−0.11	0.12
170	−0.41	0.03	**−182** ± **30**	0.12	0.56	**170**	−0.06	0.13	**−182** ± **30**	0.01	0.24
175	−0.52	−0.08	−0.12	**−186** ± **29**	0.45	**175**	−0.07	0.11	−0.01	**−183** ± **28**	0.23
190	−0.90	−0.48	−0.56	−0.45	**−199** ± **32**	**190**	−0.28	−0.12	−0.24	−0.23	**−190** ± **33**
	Hip Flexion Velocity (°·s^{-1})						**Hip Flexion Velocity (°·s^{-1})**				
	150	**165**	**170**	**175**	**190**		**150**	**165**	**170**	**175**	**190**
150	**183** ± **30**	−0.61	−0.73	−0.87	−1.37	**150**	**196** ± **27**	−0.42	−0.30	−0.19	−0.31
165	0.61	**201** ± **29**	−0.09	−0.20	−0.72	**165**	0.42	**207** ± **26**	0.12	0.24	0.12
170	0.73	0.09	**204** ± **27**	−0.11	−0.66	**170**	0.30	−0.12	**204** ± **27**	0.12	0.00
175	0.87	0.20	0.11	**207** ± **24**	−0.58	**175**	0.19	−0.24	−0.12	**201** ± **25**	−0.12
190	1.37	0.72	0.66	0.58	**221** ± **25**	**190**	0.31	−0.12	0.00	0.12	**204** ± **26**

Means ± SD are presented on the main diagonal of each table. Effect sizes for pairwise comparisons are presented in the remaining cells.

pedaling rate. With one exception, the effect sizes relating to ankle excursion were small for all comparisons (Table 4).

DISCUSSION

The purpose for conducting this study was to determine whether changes in crank length would affect the relative contributions of hip, knee, and ankle powers to overall pedal power. Our main finding was that the effect of crank length on relative joint-specific power production was dependent on the control of pedaling rate. In agreement with our hypothesis, crank length did not affect relative joint-specific powers when pedaling rate was set to optimize maximum power (matched for cyclic velocity). This finding extends previous results that overall pedal power is similar across a range of crank lengths (19) by demonstrating that pedal power is produced with similar joint-specific power contributions across crank lengths. In contrast, crank length significantly affected relative joint-specific power when pedaling rate was held constant at 120 rpm but only when comparing the shortest and longest cranks (150 and 190 mm).

When pedaling rate is constant across crank lengths, pedal speed is linearly related to crank length. Pedal speed is highly related to joint angular velocity at the hip and knee (15) and therefore serves as a surrogate measure of muscle shortening velocity at these joints (28). Consequently, our significant effect of crank length on hip and knee power in the constant pedaling rate condition could be a result of the interaction between crank length and joint angular velocity rather than an effect of crank length *per se*. This notion is supported by our analysis of joint angular velocities. When pedaling rate was held constant at 120 rpm, increased crank length resulted in a greater increase in knee flexion velocity and hip extension velocity when compared with the

TABLE 4. Joint excursions at the hip, knee, and ankle.

	Constant Pedaling Rate						Optimized Pedaling Rate				
	Ankle Excursion (°)						Ankle Excursion (°)				
	150	165	170	175	190		150	165	170	175	190
150	**34 ± 10**	−0.12	−0.08	−0.01	−0.07	**150**	**31 ± 9**	−0.44	−0.41	−0.34	−0.55
165	0.12	**35 ± 10**	0.04	0.10	0.05	**165**	0.44	**35 ± 10**	0.02	0.08	−0.14
170	0.08	−0.04	**35 ± 10**	0.06	0.01	**170**	0.41	−0.02	**35 ± 10**	0.06	−0.16
175	0.01	−0.10	−0.06	**34 ± 11**	−0.05	**175**	0.34	−0.08	−0.06	**34 ± 11**	−0.21
190	0.07	−0.05	−0.01	0.05	**35 ± 10**	**190**	0.55	0.14	0.16	0.21	**37 ± 11**
	Knee Excursion (°)						Knee Excursion (°)				
	150	165	170	175	190		150	165	170	175	190
150	**67 ± 8**	−0.50	−0.55	−0.86	−1.29	**150**	**66 ± 7**	−0.59	−0.70	−1.00	−1.44
165	0.50	**71 ± 8**	0.00	−0.27	−0.71	**165**	0.59	**70 ± 6**	−0.13	−0.44	−0.90
170	0.55	0.00	**71 ± 7**	−0.31	−0.79	**170**	0.70	0.13	**71 ± 7**	−0.29	−0.74
175	0.86	0.27	0.31	**73 ± 6**	−0.54	**175**	1.00	0.44	0.29	**73 ± 6**	−0.47
190	1.29	0.71	0.79	0.54	**77 ± 6**	**190**	1.44	0.90	0.74	0.47	**76 ± 7**
	Hip Excursion (°)						Hip Excursion (°)				
	150	165	170	175	190		150	165	170	175	190
150	**44 ± 8**	−0.50	−0.56	−0.69	−1.17	**150**	**44 ± 7**	−0.63	−0.59	−0.66	−1.04
165	0.50	**48 ± 8**	−0.04	−0.15	−0.65	**165**	0.63	**48 ± 7**	0.02	−0.03	−0.45
170	0.56	0.04	**48 ± 7**	−0.12	−0.66	**170**	0.59	−0.02	**48 ± 7**	−0.05	−0.46
175	0.69	0.15	0.12	**49 ± 6**	−0.56	**175**	0.66	0.03	0.05	**49 ± 7**	−0.42
190	1.17	0.65	0.66	0.56	**53 ± 7**	**190**	1.04	0.45	0.46	0.42	**52 ± 7**

Means ± SD are presented on the main diagonal of each table. Effect sizes for pairwise comparisons are presented in the remaining cells.

condition in which we controlled for cyclic velocity (Table 3). Further, the effect of crank length on joint excursion, which serves as an indicator of muscle length (28), of the knee and the hip did not differ between pedaling rate conditions (Table 4). Taken together, these findings support the notion that joint-specific powers are governed by joint angular velocities (and therefore the shortening velocities of muscles) across crank lengths. However, our data do not provide incontrovertible evidence for this speculation.

In previous work, Martin and Spirduso (19) demonstrated that the relationships between pedal power and cyclic velocity (pedal speed × cycle frequency) did not differ for crank lengths of 145, 170, and 195 mm. Our observation of similar joint-specific powers at a constant value of cyclic velocity substantiates on those findings and emphasizes the dual roles of pedal speed and cycle frequency in determining maximum power during cycling via two different mechanisms. Pedal speed governs the shortening velocity of muscles spanning the hip, knee, and ankle joints and thereby affects power via the force–velocity relationship of muscle (19,28). Cycle frequency governs the time within which these muscles become excited, produce force while shortening, and relax before lengthening. Thus, cycle frequency affects power via the muscle excitation–relaxation kinetics (3,15,21,27). Our present data demonstrate that the interactive effects of shortening velocity and cycle frequency cause a similar joint-specific power production at the optimal cyclic velocity. These data also suggest that cyclic velocity may affect joint-specific power production over a range of cyclic velocities, which should be the subject of future research.

Relative contributions of joint-specific powers to overall power have important implications for fatiguing exercises. Martin and Brown (14) demonstrated that during fatiguing maximal cycling, the hip extensors are more fatigue resistant than the knee extensors. Further, Tomas et al. (25) reported that fatigue is reduced when cycling with 220-mm cranks in comparison with 120-mm cranks with pedaling rates optimized for maximum power. These authors speculated that their results could be due to their participants relying more heavily on the less fatigable hip extensors when pedaling with longer cranks. Our data indicated that joint-specific powers were not affected by crank length when pedaling rate was optimized for maximum power and thus do not support this speculation. Our findings let us speculate that the reduced fatigue on longer cranks observed by Tomas et al. (25) was due to other factors, such as total work or the number of maximal muscle contractions. However, our data do not provide irrefutable evidence for this speculation because the range of crank lengths used in this study was different from that used by Tomas et al. (25).

Our findings have implications for competitive cyclists and coaches because they demonstrate that changes between cranks of standard length (165–175 mm) do not compromise maximum cycling power or modify the relative joint power contributions to pedal power. For this range of crank lengths, similarities in pedal and joint powers were observed for both methods of controlling pedaling rate. Therefore, our results suggest that cyclists can select crank lengths on the basis of other factors, such as reduced aerodynamic drag or reduced risk of injury (e.g., by controlling joint ranges of motion) without the concern of compromising their maximum power capability. Further, our findings demonstrate that once the effects of pedaling rate and pedal speed are accounted for (by matching pedaling rate for cyclic velocity), even large changes in crank length (150–190 mm) do not affect joint-specific maximal power production. These findings could have particular relevance to bicycle designs incorporating novel crank length and gearing systems. Finally, researchers investigating relative joint-specific powers can allow participants to use their preferred crank length without introducing a confounding factor to the study. This notion may be of importance for research undertaken on elite cyclists, in which it may be preferable for participants to perform experimental protocols in their accustomed cycling position.

In summary, our findings demonstrate that the effect of crank length on relative joint-specific power production is dependent on the control of pedaling rate. When pedaling rate is set to be optimal for maximum power production, changes in crank length of 150–190 mm do not affect overall cycling power or relative joint-specific powers at the hip, knee, or ankle. When pedaling rate is constant across crank lengths, extremely long cranks (190 mm) can result in less relative knee flexion power and more relative hip extension power when compared with very short cranks (150 mm). Our data support the speculation that these effects are due to variations in joint angular velocity and therefore muscle shortening velocity across the crank length range. Our results extend previous findings that crank length *per se* is not an important determinant of short-term maximum cycling power by demonstrating that crank length does not influence joint-specific maximal power production.

This work was supported by funding from the Engineering and Physical Sciences Research Council's Doctoral Training Grant scheme.

The results of the present study do not constitute endorsement by the American College of Sports Medicine.

REFERENCES

1. Askew GN, Marsh RL. Muscle designed for maximum short-term power output: quail flight muscle. *J Exp Biol*. 2002;205:2153–60.
2. Broker JP, Gregor RJ. Mechanical energy management in cycling: source relations and energy expenditure. *Med Sci Sports Exerc*. 1994;26(1):64–74.
3. Caiozzo VJ, Baldwin KM. Determinants of work produced by skeletal muscle: potential limitations of activation and relaxation. *Am J Physiol*. 1997;273(3 Pt 1):C1049–56.
4. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. Hillsdale (NJ): Lawrence Erlbaum Associates; 1988. p. 23–7.
5. de Leva P. Adjustments to Zatsiorsky–Seluyanov's segment inertia parameters. *J Biomech*. 1996;29(9):1223–30.
6. Dorel S, Couturier A, Lacour JR, Vandewalle H, Hautier C, Hug F. Force–velocity relationship in cycling revisited: benefit of two-dimensional pedal forces analysis. *Med Sci Sports Exerc*. 2010; 42(6):1174–83.
7. Dotan R, Bar-Or O. Load optimization for the Wingate anaerobic test. *Eur J Appl Physiol*. 1983;51:409–17.
8. Elftman H. Forces and energy changes in the leg during walking. *Am J Physiol*. 1939;125:357–66.
9. Hull ML, Jorge M. A method for biomechanical analysis of bicycle pedalling. *J Biomech*. 1985;18(9):631–44.
10. Inbar O, Dotan R, Trousil T, Dvir Z. The effect of bicycle crank-length variation upon power performance. *Ergonomics*. 1983;26(12): 1139–46.
11. Josephson RK. Dissecting muscle power output. *J Exp Biol*. 1999; 202(Pt 23):3369–75.
12. Marsh RL. How muscles deal with real-world loads: the influence of length trajectory on muscle performance. *J Exp Biol*. 1999;202: 3377–85.
13. Martin JC. Muscle power: the interaction of cycle frequency and shortening velocity. *Exerc Sport Sci Rev*. 2007;35(2):74–81.
14. Martin JC, Brown NA. Joint-specific power production and fatigue during maximal cycling. *J Biomech*. 2009;42(4):474–9.
15. Martin JC, Brown NA, Anderson FC, Spirduso WW. A governing relationship for repetitive muscular contraction. *J Biomech*. 2000; 33(8):969–74.
16. Martin JC, Davidson CJ, Pardyjak ER. Understanding sprint–cycling performance: the integration of muscle power, resistance, and modeling. *Int J Sports Physiol Perform*. 2007;2(1):5–21.
17. Martin JC, Diedrich D, Coyle EF. Time course of learning to produce maximum cycling power. *Int J Sports Med*. 2000;21(7):485–7.
18. Martin JC, Elmer SJ, Horscroft RD, Brown NA, Schultz BB. A low-cost instrumented spatial linkage accurately determines ASIS position during cycle ergometry. *J App Biomech*. 2007;23(3):224–9.
19. Martin JC, Spirduso WW. Determinants of maximal cycling power: crank length, pedaling rate and pedal speed. *Eur J Appl Physiol*. 2001;84(5):413–8.
20. Neptune RR, Hull ML. Accuracy assessment of methods for determining hip movement in seated cycling. *J Biomech*. 1995;28(4): 423–37.
21. Neptune RR, Kautz SA. Muscle activation and deactivation dynamics: the governing properties in fast cyclical human movement performance? *Exerc Sport Sci Rev*. 2001;29(2):76–80.
22. Patton JF, Murphy MM, Frederick FA. Maximal power outputs during the Wingate anaerobic test. *Int J Sports Med*. 1985;6:82–5.
23. Sargeant AJ. Structural and functional determinants of human muscle power. *Exp Physiol*. 2007;92(2):323–31.
24. Swoap SJ, Caiozzo VJ, Baldwin KM. Optimal shortening velocities for *in situ* power production of rat soleus and plantaris muscles. *Am J Physiol*. 1997;273:C1057–63.
25. Tomas A, Ross E, Martin JC. Fatigue during maximal sprint cycling: unique role of cumulative contraction cycles. *Med Sci Sports Exerc*. 2010;42(7):1364–9.
26. Too D, Landwer GE. The effect of pedal crank arm length on joint angle and power production in upright cycle ergometry. *J Sports Sci*. 2000;18(3):153–61.
27. van Soest O, Cassius LJ. Which factors determine the optimal pedaling rate in sprint cycling? *Med Sci Sports Exerc*. 2000; 32(11):1927–34.
28. Yoshihuku Y, Herzog W. Optimal design parameters of the bicycle–rider system for maximal muscle power output. *J Biomech*. 1990; 23(10):1069–79.
29. Yoshihuku Y, Herzog W. Maximal muscle power output in cycling: a modelling approach. *J Sports Sci*. 1996;14(2):139–57.