Determination of the optimal crank arm length to maximize peak power production in an upright cycling position

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Abstract

The purpose of this paper was to determine: (1) the crank arm length that would maximize peak power production in an upright cycling position; (2) the joint angles corresponding to this crank arm length; (3) which joint angles (minimum, maximum, range of motion of the hip, knee and ankle) would be the best predictor(s) of the crank arm length; and (4) develop regression equations to predict the optimal crank arm length for individuals of different leg lengths. The data from Too and Landwer (2000) was examined, in conjunction with the data collected in this study, and combined for use in regression analysis. With stepwise multiple regression, the following equation was determined to best predict crank arm lengths that would maximize peak power production in an upright cycling position for individuals of different leg lengths:
*CAL [mm] = (238 [mm] – 0.25 * (Tot Leg) [mm] + 0.3 * (Low Leg) [mm]) ± 22 [mm]*
As with any prediction equation, caution must be taken when interpreting and extrapolating the results.

Introduction

In the quest to improve or maximize cycling performance, various manipulations to the bicycle have often been made. Manipulations to the bicycle have included changes in seat-tube angle (Heil et al., 1995; Too, 1990, 1991), seat height (Hamley and Thomas, 1967; Nordeen-Snyder, 1977; Shennum and deVries, 1976), seat to pedal distance (Too, 1993), and crankarm length (Carmichael, 1981; Hull and Gonzalez, 1988; Inbar et al., 1983; Klimt and Voigt, 1974; Too and Landwer, 2000). These manipulations result in changes in lower extremity joint angles (i.e., hip, knee, ankle) that affect cycling performance. Based on muscle tension-length and force-velocity-power relationships, any manipulations to lower extremity joint angles (minimum, maximum, range of motion) such as changing the crank arm length will alter cycling performance by affecting variables (such as muscle length and muscle moment arm length) involved in the production of force, torque, and power. A change in joint angle, resulting in a change in muscle length, will alter the muscle force that can be produced. This change in muscle force, interacting with the change in muscle moment arm, will affect the torque and power output that is produced. Therefore, it is not the manipulation in bicycle geometry (i.e., seat tube angle, seat height, seat-to-pedal distance, crank arm length) that is important, but rather what are the joints angles associated with these manipulations? Determining the joint angles (and/or range of joint angles) that maximizes cycling performance with these manipulations is the first step that needs to be made. The next step would be to extrapolate these “optimal” joint angles into identifying the bicycle geometry, variables and manipulations that need to be made, and how it is to be made to maximize cycling performance. The final step would be to identify how to “fine tune” or individualize these manipulations to be optimum (i.e., result in the same optimal joint angles) for cyclists of different anthropometric characteristics (i.e., different height, leg length).

For an upright cycling position, it has been reported that the seat height to maximize anaerobic work of high intensity for short duration is a leg length that is 109% of the distance from the floor to the symphysis pubis (Hamley & Thomas 1967; Thomas 1967a,b). However, joint angles (over a pedal cycle) were not determined or reported. With the same leg length / seat height measurements, Too and Landwer (2000) did record and report joint angle changes (minimum, maximum, range of motion) of the hip, knee, and ankle over a pedal cycle with changes in crank arm length (from 110-265 mm), and how it affected power production. An inverted U-curve was determined to best describe the trend in peak power with incrementing crank arm length. Although a regression equation was generated to predict peak power production with changes in crank arm length (from 110 mm to 265 mm), it was not determined what the optimal crank arm length would be to maximize power production, or what the joint angles would be. It should be noted that the crank arm length predicted to maximize power production (and the corresponding joint angles associated with it) may not necessarily be the same for individuals who are taller or shorter (i.e., have longer or shorter leg lengths) than the participants in the study by Too and Landwer (2000). In other words, the “optimal” crank arm length (resulting in certain joint angles) for the participants in the study by Too and Landwer (2000) may not be optimum for individuals who have significantly longer or shorter leg lengths, and the “optimal” crank arm length may have to be proportionally adjusted to result in the same joint angles. But how the crank arm length is to be adjusted (and by what criteria) have not been determined, and would be important information to cyclists of different heights and leg lengths. Although, joint angle measurements (minimum and maximum) of the hip, knee, and ankle determined from video data by Too and Landwer (2000) is better and more accurate than static measurements obtained with hand-held goniometers from previous studies (Too, 1990, 1991, 1993) direct measurements (i.e., with electrogoniometers) are always preferable.

Based on the preceding information presented, the purpose of this paper was to determine: (1) the crank arm length that maximize power production (based on the regression equation provided by Too and Landwer (2000)); (2) the joint angles for the crank arm length that maximize power production; (3) which joint (hip, knee, ankle) and/or joint angle(s) (minimum, maximum, range of motion) would best predict the crank arm length that maximize power production, and (4) develop a regression equation to predict the optimal crank arm length to maximize power production for individuals with different anthropometric measurements (i.e., height, total leg length, upper leg length, and lower leg length). This included collection of joint angle data using electrogoniometers with crank arm lengths that are the same (110, 145, 180 mm) and different (215, 250 mm) than those (110, 145, 180, 230, 265 mm) used in the study by Too and Landwer (2000).

Methods

Participants
Seventeen healthy males age 23 ± 6.74 years (mean ± SD) volunteered to participate in the study after providing written informed consent. Their height and body mass were 1.86 ± 0.05 m and 84.7 ± 10.3 kg, respectively. Their total, upper and lower leg lengths were 0.983 ± 0.034, 0.416 ± 0.021, and 0.567 ± 0.019 m, respectively. All leg lengths were measured from the right side in a standing position, with the total, upper and lower leg lengths measured from the greater trochanter to the ground, the greater trochanter to the knee center, and the knee center to the ground, respectively. The knee center was determined visually, from observations of repeated flexion and extension of the knee. The participants were not trained cyclists, but were accustomed to cycling during daily and recreational activities.

Apparatus
All participants were tested on a free weight Monark cycie ergometer (Model 814E) at five pedal crank arm lengths (see Figure 1).

Figure 1. Monark cycle ergometer

The five crank arm lengths were 110, 145, 180, 215 and 250 mm, as defined by the distance between the center of the crank spindle and pedal axis (with 170 mm as the normal crank arm length for a Monark cycle ergometer). To accomplish this, an adjustable pedal shaft mechanism (RangeMaker™) was used, which allowed for 35 mm increments in crank arm length. RangeMaker allowed manipulation of the crank arm length from 0 to 180 mm. An additional crank allowed for a further manipulation in crank arm length from 160 to 300 mm (see Fig. 2).

Figure 2: Adjustable pedal shaft mechanism and cranks

The seat height used (where seat height is defined as the maximal distance from the pedal spindle to the top of the seat, with the crank in line with the seat tube angle) was 100% of each participant's total leg length, as measured from the greater trochanter to the floor.

Procedures

Two sessions were required of each participant and all procedures were approved by the Institutional Review Board (also referred to as the Human Subjects Review Board). The first session was use to: (1) explain the research procedures and participant involvement; (2) obtain informed consent and participant characteristics (age, height, weight, leg length); and (3) determine the appropriate seat height settings for the five different crank arm lengths (110, 145, 180, 215, 250 mm). For each participant, the test sequence for the five crank arm lengths was randomly determined.

The second session was use to record joint angles of the hip, knee, and ankle from the right side of the body using three electrogoniometers (SG150 and SG100 sensors with a K100 amplifier by Biometrics Ltd). The eletrogoniometers were attached to the skin of the trunk, thigh, leg, and foot via double stick tape, and connected to a small four channel analog amplifier that each participant wore at the waist via an integral belt clip. Cables from this amplifier were connected to a larger base unit with a power supply, where the signal was routed to an A/D box (Noraxon NorBNC), then relayed to a synchronizing unit, and finally to a laptop computer. (see Figure 3).

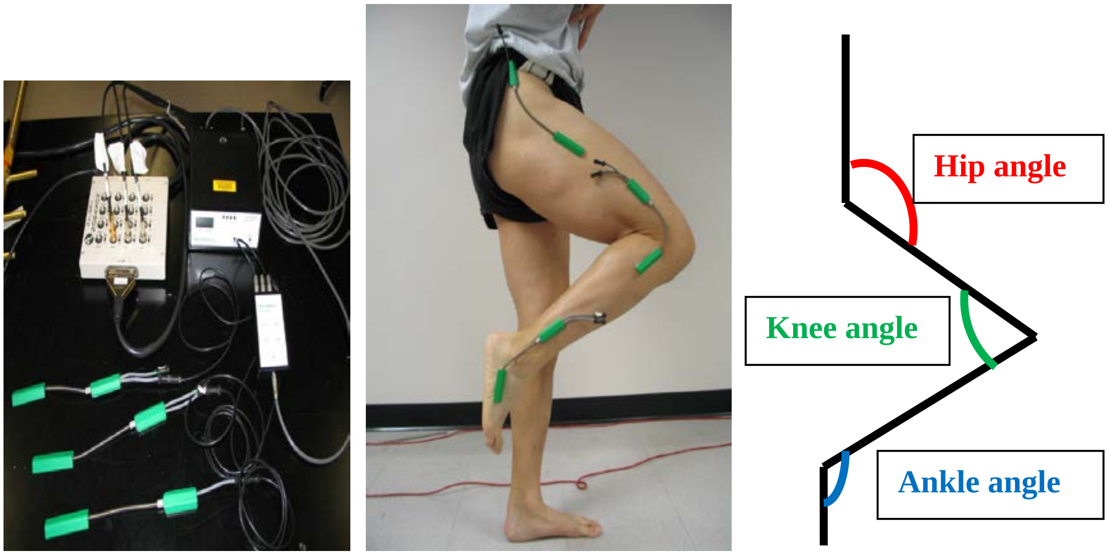


Figure 3. Electrogoniometers

For each test condition, each participant pedaled (with pedal toe-clips) at 60 rpm (in cadence with a metronome) on a Monark cycle ergometer with no load. (Note: 60 rpm was arbitrarily selected for ease of analysis where one pedal cycle was completed each second). Once the appropriate cadence was reached (which was generally within a 5-10 second period), the ergometer was loaded with 3 kg such that a power of 50 watts (W) was required to maintain 60 rpm, and data was collected for 10 seconds. For any given load, the power output (in watts) was determined as follows: Power (W) = [load (N)] x [distance covered by flywheel with one revolution (i.e., 1.615 m per revolution) x flywheel revolution per second]. Since a 3 kg mass was selected to load the ergometer and each participant's pedaling rate was 60 rpm, then the power (W) produced was calculated as follows: Power (W) = 3 kg x 9.81 m/s/s x 1.615 meters per revolution x 1 revolution per second. The power produced was approximately 47 Nm/s, 47 joules/s or 47 watts, resulting in a work output of approximately 470 joules for the 10 second data collection period.

The participant was then asked to stop pedaling, and the next test condition was set up. There was a minimum of four minutes rest between each crank arm length condition tested. A digital camcorder was use to obtain a visual record of the pedal cycles for each test condition from the right side of each participant in the sagittal plane (i.e., side view). The purpose of the digital camcorder was to provide a visual record of the study and to determine joint angles if necessary (see Figure 4). (Note: the cycling position in Figure 4 is a recumbent position, not the upright position used in this investigation, and used for illustrative purposes only).

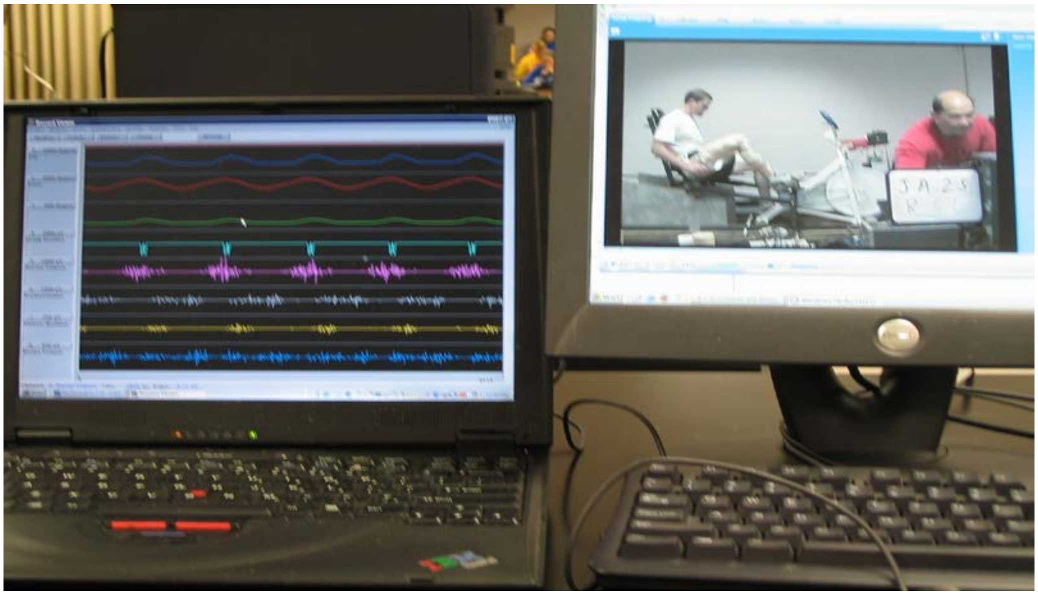


Figure 4. Equipment set-up.

Measurements

Joint angles at the hip, knee, and ankle were recorded by electrongoniometers, and determined over one complete pedal cycle/revolution. Prior to data collection, the electrogoniometers were calibrated for each participant in the standing position. In this position, the electrogoniometers of the hip and knee joint were calibrated to be 180 degrees (to represent full extension of the hip and knee). Hip and knee angles were defined by the included angle between the trunk and thigh, and thigh and lower leg, respectively. Hip and knee flexion from the standing position resulted in a decrease in angle from 180 degrees. For the ankle, the electrogoniometer was calibrated to be 90 degrees in the standing position (and defined by the included angle between the lower leg and foot). Planter flexion and dorsiflexion would be represented by angles greater than and less than 90 degrees, respectively.

For one pedal revolution, the minimum and maximum joint angle, and range of motion was determined for the hip, knee, and ankle joint in each test condition. In a pedal cycle, the minimum and maximum joint angles (hip, knee, and ankle angles) were found in the up and down stroke, respectively (with the minimum and maximum ankle angles during dorsiflexion and plantar flexion, respectively). The range of motion was determined as the difference between the maximum and minimum joint angles.

Design and Analysis

The research design consisted of a completely within subjects design (i.e., collectively as a group, each participant was compared only to himself with changes in crank arm length), with pedal crank arm length as the independent (manipulated) variable and joint angle as the dependent (measured) variable. There were nine joint angles determined over one pedal cycle and included the minimum angle, maximum angle, and range of motion of the hip, knee, and ankle. Repeated measures ANOVAs (i.e., Analysis of Variance) using SPSS (i.e., IBM SPSS Statistics 19) were used to determine whether there were significant differences in joint angles (i.e., minimum, maximum, range of motion) of the hip, knee, and ankle with 35 mm changes in crank arm length, and post-hoc tests were used to determine where these differences were.

Unpaired t-tests were used to determine whether joint angles (i.e., minimum, maximum and range of motion of the hip, knee, and ankle) with the 110, 145, and 180 mm crank arm length (used in both the study by Too and Landwer (2000) and in this investigation) were significantly different ($p < 0.05$). If significant differences were found, additional t-tests were performed on anthropometric measurements (i.e., height, total leg length, upper leg length, lower leg length) between the two studies, to determine whether joint angle differences were attributed to differences in anthropometric measurements. (An unpaired t-test, also called an independent t-test, is used to compare the values/scores between two groups, to determine if the differences found between the groups are greater than what would be expected due to chance alone).

The regression equation reported by Too and Landwer (2000) to predict peak power production from crank arm length, was used to determine the “optimal” crank arm length that maximized peak power. This crank arm length was then used to predict the corresponding the joint angles over a pedal cycle. To accomplish this, correlations between crank arm length and joint angles were determined, and regression equations generated to predict the “optimal” joint angles from this crank arm length. Multiple regression was then used to identify variables (e.g., joint angles, height, leg length) that can best predict crank arm length, and generate a series of regression equations using them to predict crank arm length.

In the current investigation, a stepwise multiple regression was also used to identify the variables (i.e., joint angles and anthropometric measurements) that best predicted crank arm length, and to generate a series of regression equations. Based on the results of the regression analysis performed on the data by Too and Landwer (2000), and of this investigation, joint angle variables were identified and used (in conjunction with anthropometric variables), to generate another series of equations to predict crank arm length from the combined data (of Too and Landwer (2000), and this investigation). These equations were used to predict the optimal crank arm length that would maximize power production for individuals with different anthropometric measurements.

Results

The following trends in joint angles were found with incrementing crank arm lengths: (1) decreasing minimum hip and knee angle; (2) increasing range of motion of the hip and knee; (3) increasing minimum ankle angle (which was unexpected), and (4) decreasing ankle angle range of motion (which was also unexpected) (see Table 1 and Figures 5-7). Repeated Measures ANOVAs revealed there were significant differences ($p < 0.01$) in the minimum joint angle and joint range of motion for the hip, knee, and ankle with incrementing crank arm length.

Table 1。Hip, Knee, and Ankle Joint Angles at Five Crank Arm Lengths (Mean±SE)

	Crank Arm Length (mm)				
	110	145	180	215	250
Hip (deg)					
*Min	121.8 ± 3.43	111 ± 3.97	101.7 ± 4.68	91.8 ± 5.67	86.9 ± 6.29
Max	160.9 ± 2.09	162.4 ± 2.42	164.3 ± 2.17	161.5 ± 2.67	164.7 ± 2.64
*ROM	37.9 ± 3.61	50.5 ± 2.95	61.4 ± 4.22	69 ± 4.81	77.4 ± 5.63
Knee (deg)					
*Min	102.2 ± 4.34	87.7 ± 4.78	74.4 ± 4.93	63.6 ± 5..22	56.3 ± 5.66
Max	157.2 ± 3.84	153.5 ± 3.69	151.4 ± 5.41	147.6 ± 5.68	147.9± 6.95
*ROM	55 ± 4.28	65.8 ± 4.3	77.1 ± 5.73	84 ± 5.94	91.5 ± 6.62
Ankle (deg)					
*Min	84.3 ± 2.47	87.8 ± 2.13	91.5 ± 2.58	93.2 2.67	93.9 2.47
Max	117.2 ± 3.51	115.4 ± 3.62	115.9 ± 3.78	116.8 ± 3.12	118.3 ± 3.71
*ROM	32.9 ± 3.8	27.5 ± 3.16	24.3 ± 2.76	23.6 ± 2.52	24.4 ± 2.7

Min = Minimum
Max = Maximum
ROM = range of motion
* ($p < 0.01$)

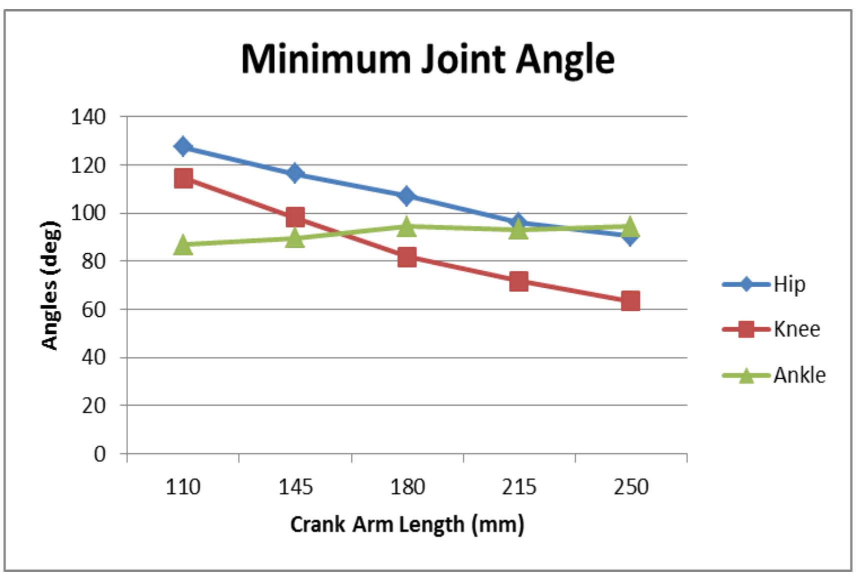


Figure 5: Minimum joint angle with changes in crank arm length

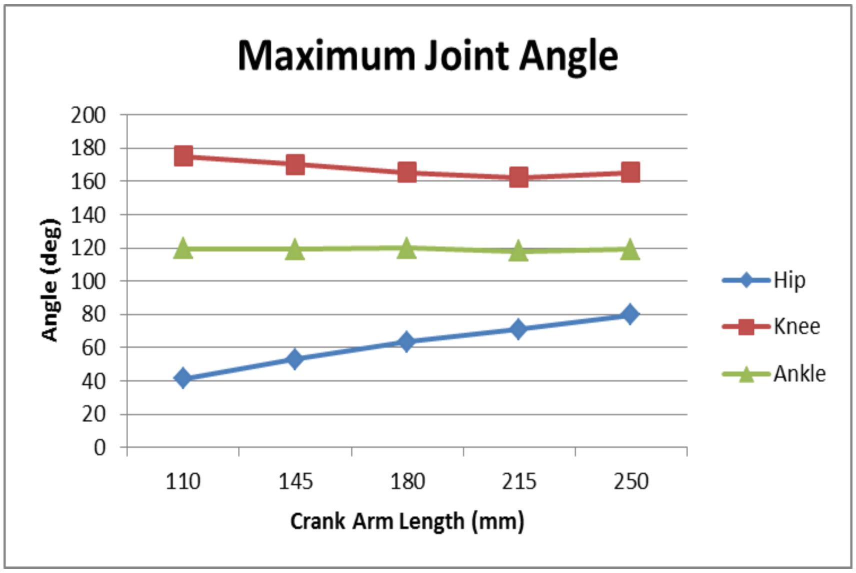


Figure 6: Maximum joint angle with changes in crank arm length

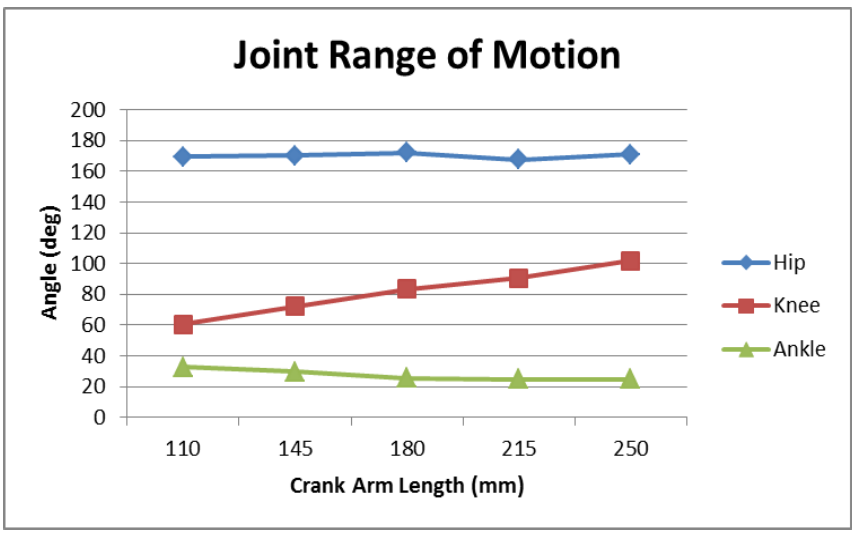


Figure 7: Joint range of motion with changes in crank arm length

Post-hoc tests revealed a significant ($p < 0.05$): (1) decrement in the minimum hip and knee angle for each 35 mm increment in crank arm length; (2) increment in the hip and knee range of motion for each 35 mm increment in crank arm length; (3) increment in the minimum ankle angle between the 145 mm and 180 mm crank arm length; and (4) decrement in the ankle angle range of motion between the 110 mm and 145 mm crank arm length, and between the 145 mm and 180 mm crank arm length (see Table 2). (The trend of increasing minimum ankle angle, and decreasing ankle angle range of motion with increasing crank arm length was unexpected and quite contrary to the trend of decreasing minimum hip and knee angle, and increasing hip and knee range of motion with increasing crank arm lengths from 110-250 mm).

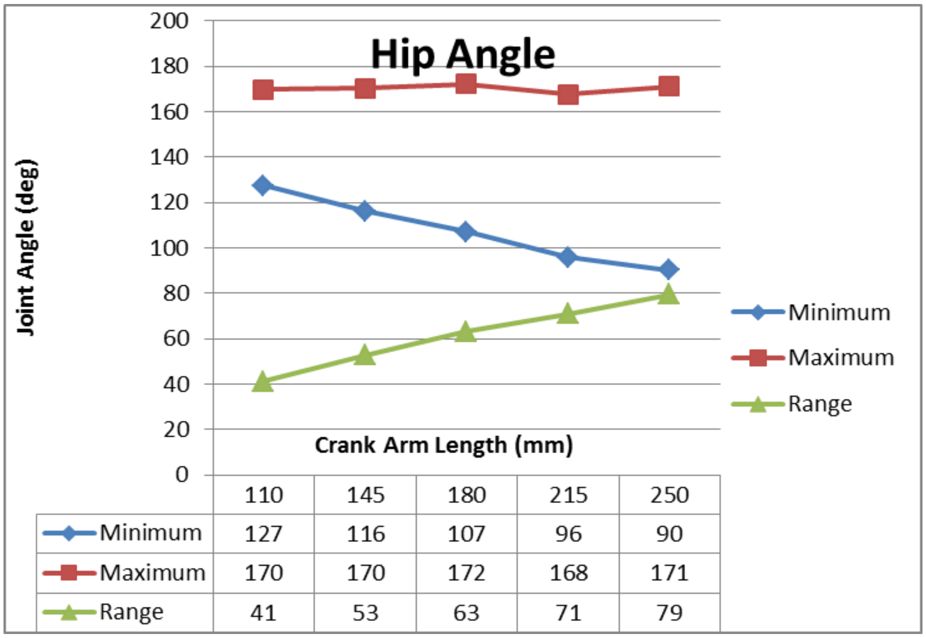
Table 2. Post-hoc test p-values for significant main effects of crank arm length

	110 vs. 145	145 vs. 180	180 vs. 215	215 vs. 250
Hip Angle (deg)				
Min	0.000	0.002	0.002	0.008
Max	N/A	N/A	N/A	N/A
ROM	0.000	0.000	0.002	0.000
Knee Angle (deg)				
Min	0.000	0.000	0.000	0.004
Max	N/A	N/A	N/A	N/A
ROM	0.000	0.000	0.000	0.008
Ankle Angle (deg)				
Min	0.101	0.012	0.168	0.580
Max	N/A	N/A	N/A	N/A
ROM	0.002	0.003	0.276	0.332

Crank Arm Length (mm)

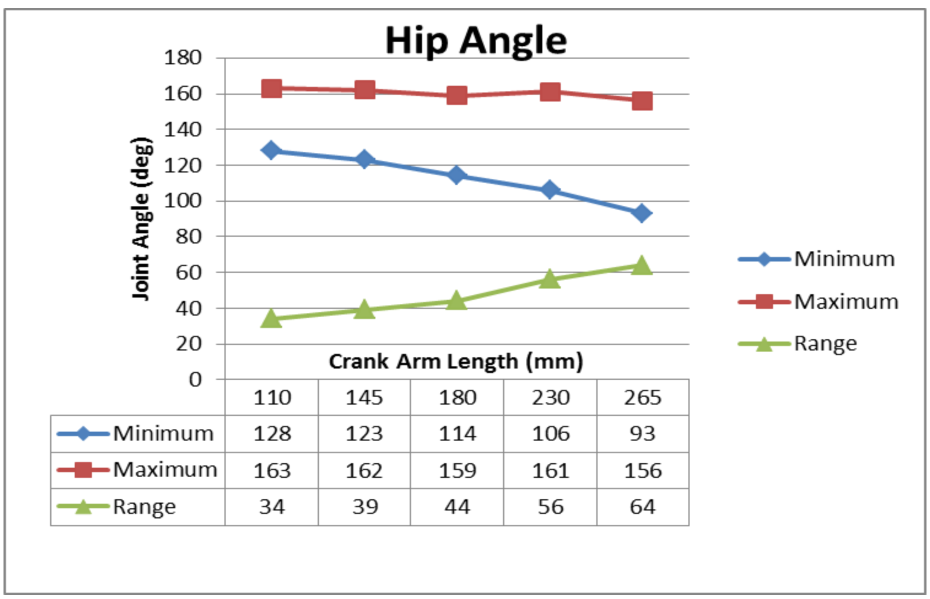
Min = Minimum
Max = Maximum
ROM = range of motion
N/A = not applicable due to non-significant main effect

In a comparison of the joint angles of the current investigation (using crank arm lengths of 110, 145,180, 215, and 250 mm) with that of Too and Landwer (2000) (using crank arm lengths of 110, 145,180, 230, and 265 mm), the results and trend with changes in crank arm length were fairly similar (see Figures 8- 13).



	110	145	180	215	250
Minimum	127	116	107	96	90
Maximum	170	170	172	168	171
Range	41	53	63	71	79

Figure 8: Hip angle with changes in crank arm length (**Current investigation)**



	110	145	180	230	265
Minimum	128	123	114	106	93
Maximum	163	162	159	161	156
Range	34	39	44	56	64

Figure 9: Hip angle with changes in crank arm length (**Too & Landwer, 2000**)

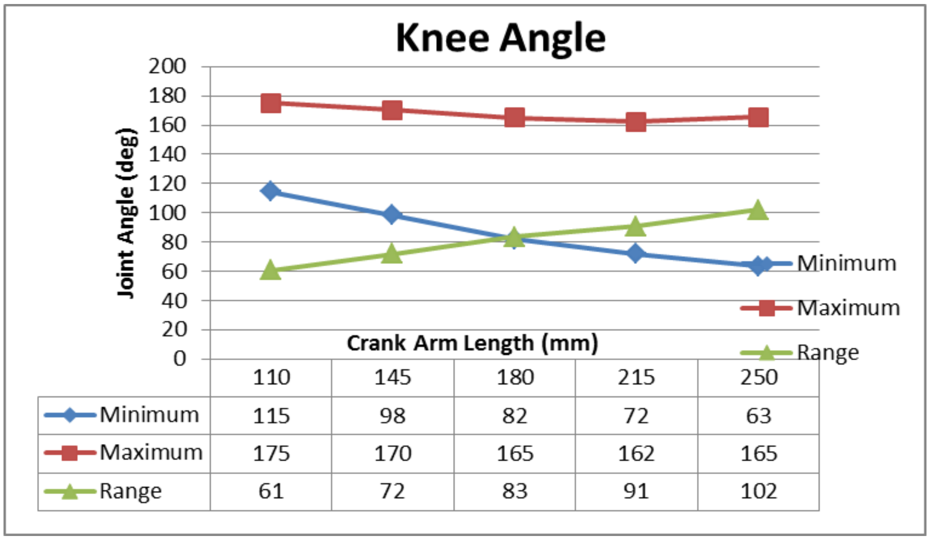


Figure 10: Knee angle with changes in crank arm length (**Current investigation**)

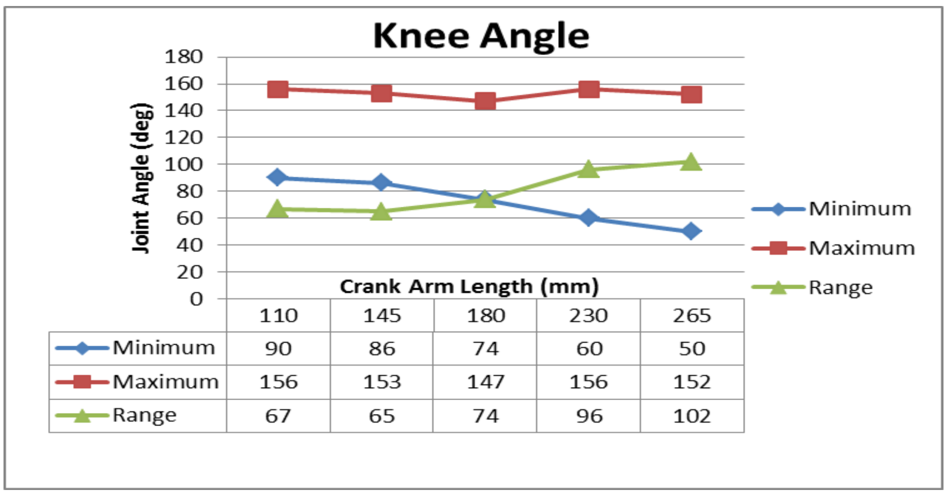


Figure 11: Knee angle with changes in crank arm length (**Too & Landwer, 2000**)

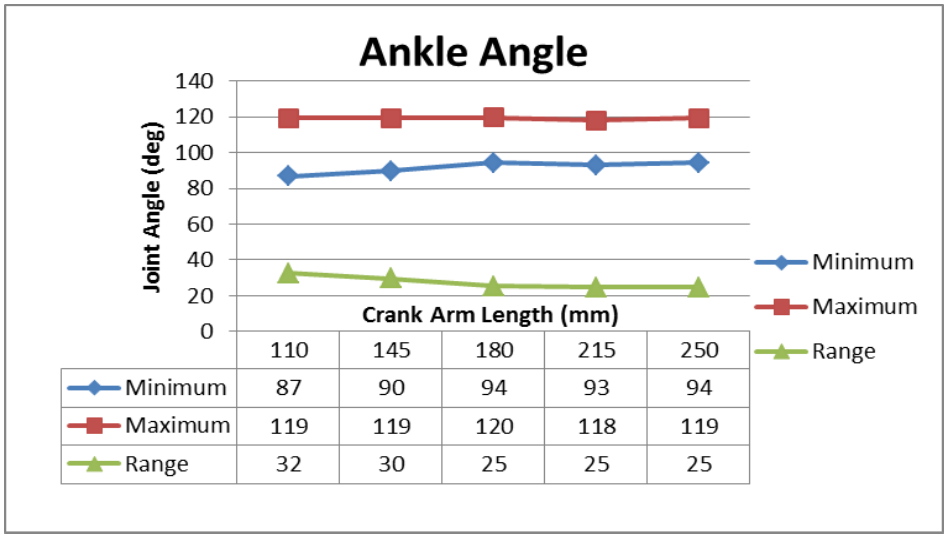


Figure 12: Ankle angle with changes in crank arm length (**Current investigation**)

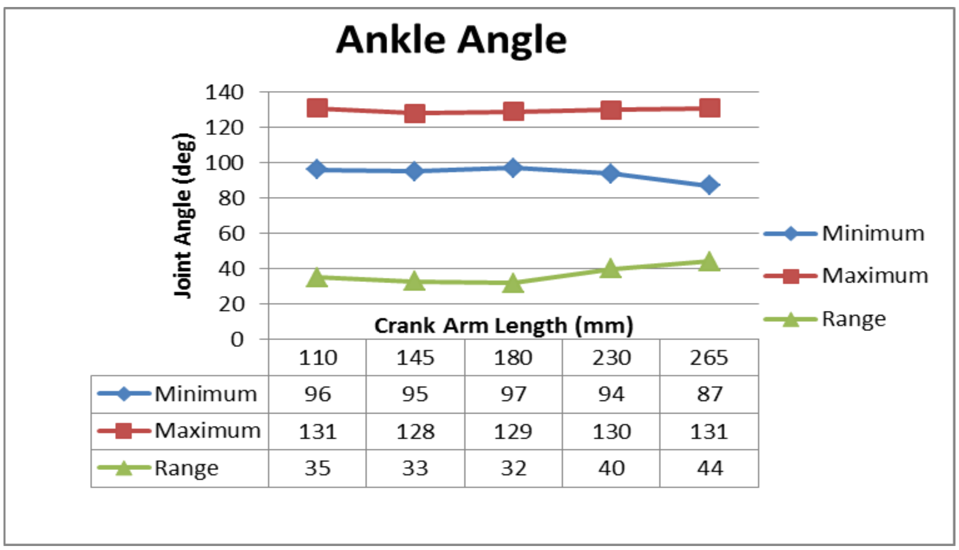


Figure 13: Ankle angle with changes in crank arm length (**Too & Landwer, 2000**)

Unpaired t-tests compared the joint angles (minimum, maximum, range of motion) of the hip, knee, and ankle for the same 110, 145, and 180 mm crank arm lengths between the participants in the current investigation and those in the study by Too and Landwer (2000) (see Table 3). The t-test results revealed signficant differences ($p < 0.05$) between groups in all three crank arm lengths for the maximum hip angles, hip range of motion, and maximum knee angle. The minimum knee angle was significantly different ($p < 0.05$) between the two groups for the 110, 145 mm crank arm lengths, and the ankle minimum angle. The ankle range of motion was only significantly different between the groups for the 110 mm crank arm length only. These significant differences may be attributed to differences in: (1) the seat height used by Too and Landwer (2000) (i.e., 109% of each participant's lower extremity length, as measured from the symphysis pubis to the floor) when compared to the leg length used in the current study (i.e. 100% of leg length from the greater trochanter to the ground); (2) height; (3) total leg length; and/or (4) lower leg length between the participants tested by Too and Landwer (2000) and the participants in the current study (see Table 4).

Table 3. Unpaired t-test results comparing joint angles with 110, 145, and 180 mm crank arm lengths (Too & Landwer versus Current Study)

		Too & Landwer	vs	Current Study		
Hip Angle						
	Crank arm length (mm)	Minimum (deg)			p-value	
	110 mm	126		127	0.813	
	145 mm	119		116	0.409	
	180 mm	112		107	0.325	
		Maximum (deg)				
	110 mm	157		170	0.002	**
	145 mm	155		170	0.001	**
	180 mm	154		172	0.000	**
		Range of Motion (deg)				
	110 mm	30		41	0.029	*
	145 mm	36		53	0.001	**
	180 mm	43		63	0.005	**
Knee Angle						
	Crank arm length (mm)	Minimum (deg)				
	110 mm	98		115	0.006	**
	145 mm	86		98	0.036	*
	180 mm	74		82	0.165	
		Maximum (deg)				
	110 mm	149		175	0.000	**
	145 mm	148		170	0.000	**
	180 mm	148		165	0.025	*
		Range of Motion (deg)				
	110 mm	51		61	0.118	
	145 mm	62		72	0.063	
	180 mm	74		83	0.183	
Ankle Angle						
	Crank arm length (mm)	Minimum (deg)				
	110 mm	103		87	0.000	**
	145 mm	96		90	0.079	
	180 mm	97		94	0.536	
		Maximum (deg)				
	110 mm	121		119	0.802	
	145 mm	120		119	0.958	
	180 mm	119		120	0.929	
		Range of Motion (deg)				
	110 mm	17		32	0.005	**
	145 mm	23		30	0.189	
	180 mm	22		25	0.513	
* $p < 0.05$						
** $p < 0.01$						

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Table 4 Umpaired t-test results comparing anthropometric measurements (Too & Landwer versus Current Study)

	Too & Landwer	Current Study	p-value	
Age (yrs)	26.6	23.0	0.079	
Weight (kg)	79.6	84.7	0.192	
Height (m)	1.79	1.86	0.030	*
Total leg length (m)	0.93	0.98	0.012	*
Upper leg length (m)	0.40	0.42	0.283	
Lower leg length (m)	0.53	0.57	0.001	**

* $p < 0.05$

** $p < 0.01$

With increasing in crank arm length from 110 to 265 mm, Too and Landwer (2000) reported that peak power appeared to be described best by a parabolic curve (see Figure 14), represented by the equation:

$$\text{Peak Power [W]} = 635\text{ W} + a * \text{CAL [mm]} - b * \text{CAL}^2\,[\text{mm}^2] \pm 11\text{ W}$$

with: CAL = crank arm length, $a = 4$ W/mm, $b = 0.012$ W/mm^2

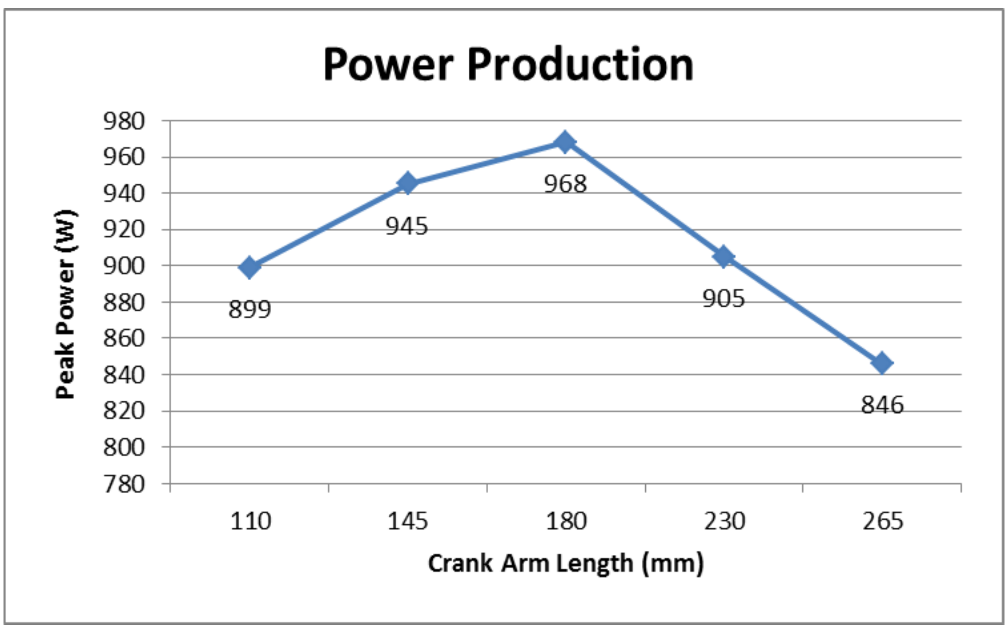

Figure 14: Peak power with changes in crank arm length (**Too & Landwer, 2000**)

To determine the crank arm length that would maximize peak power, 1 mm increments in crank arm lengths (from 110 to 265 mm) were used in the equation. It was calculated that the largest peak power would be produced with a crank arm length of 174 mm. To determine what joint angles would be expected with a crank arm length of 174 mm, regression equations were generated to predict the following joint angles (in degrees) from crank arm length (see Table 5).

Table 5: Regression Equations to predict joint angles from crank arm length (data from Too & Landwer, 2000)

Predicted angle (deg) with a 174 mm CAL	Joint angle (deg)	Regression Equation	± SE	R-square	r	sig
113	Min Hip =	151.7 – 0.225 (CAL)	5.87	0.827	-0.9092	0.000
156	Max Hip =	156.2 - 0.00386 (CAL)	5.38	0.0016	-0.04	0.384
43	Hip ROM =	4.61 + 0.22 (CAL)	4.08	0.906	0.9518	0.000
78	Min Knee =	129.3 - 0.296 (CAL)	5.31	0.91	-0.954	0.000
150	Max Knee =	142.5 + 0.043 (CAL)	6.67	0.12	0.346	0.005
72	Knee ROM =	13.12 + 0.34 (CAL)	4.94	0.939	0.969	0.000
98	Min Ankle =	105.4 - 0.045 (CAL)	9.03	0.0753	-0.274	0.021
161	Max Ankle =	115.8 + 0.259 (CAL)	10.8	0.018	0.134	0.163
23	Ankle ROM =	10.38 + 0.0716 (CAL)	11.9	0.105	0.32	0.008

CAL - crank arm length (mm)
Min - Minimum joint angle (deg)
Max - Maximum joint angle (deg)
ROM - range of motion (deg)
SE - standard error of prediction (deg)
R-square is the percentage of variance accounted for in joint angle by crank arm length
r - correlation between joint angle and crank arm length
sig - significance of correlation between joint angle and crank arm length

From Table 5, the largest joint angle correlations with crank arm length (i.e., $r > 0.90$) were the minimum hip angle ($r = -0.91$), hip range of motion ($r = 0.95$), minimum knee angle ($r = -0.95$), and knee range of motion ($r = 0.97$), with the corresponding joint angles to be 113, 43, 78, and 72 degrees, respectively. To identify which of these variable(s) would be the best predictor(s) of crank arm length, several equations were generated from stepwise multiple regression with all joint angle variables (i.e., minimum angle, maximum angle, range of motion angle of the hip, knee, and ankle) and anthropometric measurements (i.e., height, total leg length, upper leg length, lower leg length) included for selection. The equations generated are presented in Table 6.

	Table 6. Stepwise Multiple Regression to predict crank arm length (data from Too & Landwer, 2000)				
Model	Regression Equation	SE	R-square	R	
1	CAL = -25 + 2.76 (Knee ROM)	14.08	0.939	0.969	
2	CAL = -158 + 2.05 (Knee ROM) - 1.17 (Hip Min)	11.38	0.961	0.98	
3	CAL = -49.81 + 2.17 (Knee ROM) - 0.997 (Hip Min) + 44.4 ht	11.02	0.964	0.982	
	CAL - crank arm length (mm)				
	Knee ROM - knee range of motion (deg)				
	Hip Min - minimum hip angle (deg)				
	ht - height (m)				
	SE - standard error of prediction (mm)				

From the various regression equations in Table 6, the knee range of motion and the minimum hip angle were the two variables determined to best predict crank arm length (i.e., model 2). The equation of CAL [mm] = (-158 [mm] + 2.05 * (Knee ROM) [deg] - 1.17 * (Hip Min) [deg]) ± 7 [mm] accounted for 96.1% of the variability in the prediction of crank arm length (i.e., $R^2 = 0.961$) when the knee range of motion and minimum hip angle were selected. The addition of height to the equation (i.e., model 3) only increased the accuracy of prediction by 0.3% (to where $R^2 = 0.964$). If the "optimal" minimum hip angle (of 113 degrees) and "optimal" knee range of motion (of 72 degrees) were used in the regression equation (i.e., model 2), the predicted "optimal" crank arm length would be 173.3 mm (± 11 mm), which would be the same crank arm length predicted (i.e., 174 mm) to maximize peak power in the study by Too and Landwer, 2000).

For the current investigation, multiple regression analysis was also used to identify the variable(s) that would be the best predictor(s) of crank arm length. Stepwise multiple regression analysis was used to generate equations from joint angles (i.e., minimum, maximum, and range of motion of the hip, knee, and ankle) and anthropometric measurements (i.e., height, total leg length, upper leg length, lower leg length to predict crank arm length). The regression equations generated are presented in Table 7.

Table 7. Stepwise Multiple Regression to predict crank arm length (Current Study)					
	Model	Regression Equation	SE	R-square	R
	1	CAL = -23 + 1.899 (Knee ROM)	31.88	0.626	0.791
	2	CAL = -230 + 1.4 (Knee ROM) - 1.495 (Hip Min)	15.64	0.915	0.957
	3	CAL = -365.3 + 1.5 (Knee ROM) - 1.605 (Hip Min) + 608.4 Tot Leg	7.44	0.982	0.991
		CAL - crank arm length (mm)			
		Knee ROM - knee range of motion (deg)			
		Hip Min - minimum hip angle (deg)			
		Tot Leg - total leg length (m)			
		SE - standard error of prediction (mm)			

From Table 7, the variables selected to best predict crank arm length were the minimum hip angle, knee range of motion, and total leg length. The equation (model 3) that would best predict crank arm length was determined to be CAL [mm] = (-365.3 [mm] + 1.501 * (KneeROM) [deg] -1.605 * (HipMin) [deg] + 0.61* (TotLegLength) [mm] ± 7 [mm]. Collectively, the knee angle range of motion, minimum hip angle, and total leg length accounted for 98.2% of the variance in the prediction of crank arm length (i.e., R^2 = 0.982). Compared to model 2, the inclusion of total leg length in the regression equation (model 3) increased the variance accounted for in the prediction of crank arm length by 6.7% (from.0.915 to 0.982), and increased the correlation between the 3 predictor variables and crank arm length from 0.957 to 0.991. If the “optimal” minimum hip angle (of 113 degrees) and knee range of motion (of 72 degrees) to maximize peak power were used in the equation (i.e., model 2), the predicted crank arm length would be 162 ± 16 mm (which is different [but within the standard error] from the 174 mm crank arm length predicted to maximize peak power, as determined by the regression equation from Too and Landwer (2000). However, if total leg length was included in the regression equation (i.e., model 3), the predicted crank arm length would be 159 ± 7 mm, which is 15 mm less than the “optimal” crank arm length of 174 mm (and more than 2 standard error different). This may be attributed to the significantly (p = 0.012) greater leg length of the participants in the current study (i.e., 0.98 m) when compared to the leg length (i.e., 0.93 m) of the participants in the study by Too and Landwer (2000).

To determine a regression equation to predict crank arm length while accounting for differences in anthropometric characteristics, the data from Too and Landwer (2000) was combined with the data from the current investigation. This involved joint angle measurements from seven crank arm lengths (110, 145, 180, 215, 230, 250, 265 mm) and 28 participants. Since regression analysis (see Tables 6 and 7) revealed that the minimum hip angle and knee joint range of motion were the best predictors of crank arm length for the study by Too and Landwer (2000) and for the current investigation, these variables were selected for inclusion in a regression analysis, along with height, total leg length, upper leg length, and lower leg length. The series of equations generated with stepwise multiple regression analysis to predict crank arm length are presented in Table 8.

Table 8. Stepwise Multiple Regression to predict crank arm length (combined data from Too & Landwer (2000) and current study)

Model	Regression Equation	SE	R-square	R
1	CAL = 71.59 + 1.346 (Knee ROM)	45.48	0.322	0.575
2	CAL = 236 + 2.207 (Knee ROM) - 240.7 (Tot Leg)	29.6	0.713	0.848
3	CAL = 490 + 1.423 (Knee ROM) - 275.1 (Tot Leg) - 1.458 (Hip Min)	24.72	0.8	0.898
4	CAL = 295 + 1.52 (Knee ROM) - 246.9 (Tot Leg) - 1.471 (Hip Min) + 303 (Low Leg)	22.02	0.841	0.921
5	CAL = 338 + 1.487 (Knee ROM) - 485.2 (Tot Leg) - 1.546 (Hip Min) + 355 (Low Leg) + 408 (Upp Leg)	21.42	0.849	0.927
	CAL - crank arm length (mm)			
	Knee ROM - knee range of motion (deg)			
	Hip Min - minimum hip angle (deg)			
	Tot Leg - total leg length (m)			
	Upp Leg - upper leg length (m)			
	Low Leg - lower leg length (m)			
	SE- standard error of prediction (mm)			

From Table 8, five equations were generated with regression analysis. With each successive model, variables were added to the equation if it contributed significantly at the 0.05 level. Based on all factors considered (i.e., number of subjects/participants, standard error in prediction, R values, R^2 values, and change in R^2 values with each successive model), the regression equation from model 3 or 4 would be the most appropriate one(s) to use in the prediction of crank arm length. Model 3 with the inclusion of only three variables (i.e., hip minimum, knee range of motion, and total leg length) has a multiple correlation with crank arm length of 0.898, and can account for 80% (i.e., $R^2 = 0.8$) of the variance in prediction of crank arm length. The addition of lower leg length (model 4) only increased the correlational value by 0.023 (from 0.898 to 0.921) and increased the total variance in prediction of crank arm length by 4% (i.e., R^2 from 0.80 to 0.841). Although the inclusion of the upper leg length (model 5) did contribute significantly at the 0.05 level, the increase in the multi-correlational value (i.e., R) and R^2 value was minimal (i.e., 0.006 and 0.008 [0.8%], respectively), which is not meaningful.

If model 3 was used to predict the "optimal" crank arm length to maximize peak power using the "optimal" minimum hip angle of 113 degrees, and "optimal" knee range of motion of 72 degrees, the regression equation of
CAL [mm] = (490 [mm] + 1.423 * (Knee ROM) [deg] – 0.28 * (Tot Leg) [mm] - 1.458 * (Hip Min) [deg]) ± 25 [mm] would be reduced to:
CAL [mm] = (428 [mm] – 0.28 * (Tot Leg) [mm]) ± 25 [mm].

With this equation, if a cyclist had a total leg length of 960 mm, the predicted "optimal" crank arm length to maximize peak power would be 163 mm with a standard error of prediction of 25 mm. On the other hand, if model 4 was used, the regression equation of
CAL [mm] = (295 [mm] + 1.52 * (Knee ROM) [deg] – 0.25 * (Tot Leg) [mm] - 1.471 * (Hip Min) [deg] + 0.3 * (Low Leg) [mm]) ± 22 [mm] would be reduced to

CAL[mm] = (238 [mm] – 0.25 * (Tot Leg) [mm] + 0.3 * (Low Leg) [mm]) ± 22 [mm], and if a cyclist had a total leg length of 960 mm, and a lower leg length of 550 mm, the predicted crank arm length to maximize peak power would be 168 mm with a standard error of prediction of 22 mm.

Discussion

From previous investigations on upright cycling performance, a curvilinear trend (i.e., inverted U-shaped curve) best described anaerobic performance (i.e., peak power, mean power) with increasing crank arm lengths from 110-265 mm (with the 180 mm crank arm length resulting in the largest anaerobic cycling performance) (Too & Landwer, 2000). With increments in crank arm length, the minimum joint angles (of the hip and knee) linearly decreased, whereas the range of motion linearly increased. However, there was no information provided regarding whether the change in joint angles with a systematic change (i.e., 35 mm) in crank arm length would be significantly different (since a systematic increase in crank arm length did not necessarily result in a systematic or significant change in cycling performance).

<u>Hip and Knee Joint Angles with Changes in Crank Arm Length</u>
The results of this investigation reveal that the changes in the minimum joint angle and range of motion of the hip, knee, ankle with 35 mm changes in crank arm length were significant, with the interactions between the hip and knee angles being more complex than previously believed, and appears to be affected by the relative length of the upper and lower leg. Due to the shorter upper leg length (0.416 m) when compared to the lower leg length (0.567 m).of the participants in this investigation, the hip and knee angles did not necessarily change the same way or by the same amount with each 35 mm change in crank arm length. For example, from Table 1, there is a significant main effect ($p < .01$) and an apparent decreasing trend for the minimum hip and knee joint angle with increasing crank arm length (from 110 -250 mm). However, what is not so apparent is the difference in the rate that the minimum hip and knee angle decreases with incrementing crank arm length (and the relationship between the minimum hip and knee angle). With crank arm lengths from 110-250 mm, the minimum hip angle decreased from 121.8 degrees to 86.9 degrees (a difference of 34.9 degrees), whereas the minimum knee angle decreased from 102.2 degrees to 56.3 degrees (a difference of 80.8 degrees). (In addition, with each 35 mm change in crank arm length [from 110 to 145 to 180 to 215 to 250 mm], there was not an equivalent change in the minimum knee angle because the minimum knee angle decreased 14.5, 13.3, 11.1, and 7.3 degrees, respectively).

This would suggest that single joint muscles of the hip involved in extension (e.g., gluteus maximus) may be more (or less) involved/active during the extension/force production phase of a pedal cycle with different crank arm lengths, when compared to single joint muscles of the knee involved in extension (i.e., vastus medialis, vastus lateralis, vastus intermedius). This would also suggest that multi-joint muscles that extend the hip and flex the knee (i.e., hamstrings) or extend the knee and flex the hip (i.e., rectus femoris) would be more (or less) involved/active over a different portion and/or percentage of the muscle tension-length curve to produce more (or less) force (and power) during a pedal cycle with changes in crank arm length. This complexity is further increased when hip and knee angles changed at different rates and to a different degree due to different upper and lower leg lengths.

To determine the single and multi-joint muscle contributions of the hip and knee during a pedal/crank cycle with changes in crank arm length would require the use of EMG (i.e., electromyography to monitor the muscle activity patterns of different muscles) in conjunction with ELGONS (i.e., electrogoniometers to monitor joint angles) and a micro-switch to monitor crank position during a pedal cycle. This would provide information regarding why certain crank arm lengths are more effective based on joint angles as a result of muscle tension-length relationships, crank position, and muscle activity patterns.

<u>Ankle Joint Angles with Changes in Crank Arm Length</u>

Due to the unexpected trend in ankle joint angles (i.e., minimum, range of motion) with changes in crank arm length, and the force/power production potential of the ankle in contributing to cycling performance at different crank arm lengths, a separate section for discussion on this has been included.

For the minimum ankle angle, it appears that with 35 mm increments in crank arm length (from 110 -250 mm), the minimum ankle angle increased instead of decreased, and the ankle range of motion decreased instead of increased. This was unexpected and opposite the trend expected and that occurred with the minimum angle and range of motion of the hip and knee joint with increasing crank arm length. The minimum ankle angle also changed from a dorsiflexed position with a 145 mm crank arm length, to a plantar flexed position with a 180 mm crank arm length. There are several possible explanations for why the minimum ankle joint angle increased with increasing crank arm lengths, and changed from a dorsiflexed position to a plantar flexed one as the crank arm length is increased from 145 mm to 180 mm. These explanations include: (1) insufficient flexibility of the ankle and/or physical constraints/limitations to dorsiflex (due to the structure of the ankle joint) as the crank arm length is increased; (2) greater ankle force production potential (in a more effective portion/range of the force-length curve) as the minimum ankle joint angle increased (from a dorsiflexed position to a plantar flexed one); and (3) increased ankle joint angles to a plantar flexed position (with longer crank arm lengths) alters the joint angles to allow the larger hip and knee muscles to more effectively produce force (i.e, changes the length of the hip and knee muscles so it is in a more effective portion of the tension-length curve to produce force). The transition from a dosiflexed position with the 110 mm crank arm length to a plantar flexed position with a 180 mm crank arm length (for the minimum ankle angle) may be a reason for the trend in decreasing ankle range of motion with increasing crank arm lengths, and an explanation why the longer 230 mm crank arm length resulted in the longest cycling duration in an upright position when compared to other crank arm lengths (Too & Landwer, 1999).

To better understand why the minimum ankle angle increases with increasing crank arm length (instead of decreasing, as found with the hip and knee joint angles), and how this might affect the hip and knee angle, and cycling performance, it would be important to determine (during a pedal cycle): (1) if the crank arm is in the same position for the minimum joint angles (i.e., hip, knee, ankle) with different crank arm lengths; and if not, then (2) what is the crank arm position for the minimum hip, knee, and ankle joint angles with different crank arm lengths; and (3) what are the joint angles of the hip, knee, and ankle when the crank position is at a 0 degree position (i.e, top dead center position where the crank arm is perpendicular to the ground), 90 degrees (i.e., crank arm rotated forward 90 degrees and is parallel to the ground), 180 degrees (i.e., bottom dead center position where the crank arm perpendicular to the ground); and 270 degrees (i.e., crank arm rotated another 90 degrees from the dead center position and is parallel to the ground). This information (along with angle-angle plots of the hip-knee and knee-ankle over a pedal cycle with different crank arm lengths) will provide a more complete picture regarding how the different joint angles change during a pedal cycle with different crank arm lengths, and how the joint angles (and muscle length) may be interacting with the crank arm (based on crank arm position in a pedal cycle) to produce force/torque with different crank arm lengths. This will also provide information regarding why certain crank arm lengths are more effective that other crank arm lengths in producing force/torque/power and affecting cycling performance with changes in seat height.

<u>Implications and Applications</u>

For builders of human powered vehicles (HPVs) in the upright cycling position, the results of this investigation, in conjunction with those of previous investigations (Too & Landwer, 1999, 2000), revealed that there is not one specific crank arm length that will maximize cycling performance, but rather, a range of crank arm lengths. The range of crank arm lengths selected to maximize cycling performance will be dependent on the type of performance desired (i.e., anaerobic performance as defined by peak power and mean power, or aerobic performance as defined by cycling duration) and dependent on the total, upper, and lower leg length of the cyclist (since it is not so much the crank arm length that is important, but rather, it is the joint angles as a result of the crank arm length selected). Since, for most individuals, it is not necessarily feasible or practical to select crank arm lengths based on “trial and error” to attain joint angles similar to those reported in this investigation, regression equations were generated to determine the crank arm length to maximize cycling performance (i.e., peak power) and to account for individual differences in leg length. Since regression equations are prediction equations with inherent errors in accuracy of prediction, it is important to understand the limitations of regression equations, how to interpret them, and the caution that needs to be taken in extrapolation of the results to different populations. The logic, rationale, explanation and sequence in how the regression equations were developed are described as follows.

First, the results of the investigation by Too and Landwer (2000) on how different crank arm lengths (110, 145, 180, 230, 265 mm) affect anaerobic cycling performance (peak power, mean power), reveal that an inverted U-shape curve best describe the trend in power output with incrementing crank arm length. Peak power and mean power with repeated measures ANOVAs were reported to be significantly different ($p < 0.01$) and greater with the 180 mm crank arm length than with the other crank arm lengths, and post-hoc tests revealed that peak power and mean power with the 180 mm crank arm length was not significantly different ($p = 0.483$ and 0.221, respectively) than with the

145 mm crank arm length (Too & Landwer, 2000). Too and Landwer (2000) suggested that the optimal crank arm length (to optimize joint angles) to maximize anaerobic cycling performance would vary somewhere between 145 mm and 180 mm.

Second, using the regression equation reported by Too and Landwer (2000), it was calculated that the 174 mm crank arm length would maximize peak power. This 174 mm crank arm length was calculated (based on regression analysis) to result in the following joint angles: minimum hip angle of 113 degrees, hip range of motion of 43 degrees, minimum knee angle of 78 degrees, and knee range of motion of 72 degrees. With additional regression analysis, the following regression equation would best predict crank arm length for the data from Too and Landwer (2000): CAL [mm] = (-158 [mm] + 2.05 * (Knee ROM) [deg] - 1.17 * (Hip Min) [deg]) ± 11 [mm]. However, caution must be taken since this regression equation may be limited in scope to those with similar leg length characteristics as the subjects/participants in the study by Too and Landwer (2000).

Third, in the current investigation, the regression equation determined to best predict crank arm length was: CAL [mm] = (-365 [mm] + 1.501 * (KneeROM) [deg] -1.605 * (HipMin) [deg] + 0.61 * (TotLegLength) [mm] ± 7 [mm]. Based on this equation, the crank arm length predicted to maximize peak power (with optimal joint angles and leg length accounted for), resulted in a crank arm length of 159 mm. This meant that individuals with different leg length characteristics may need to adjust selection of their crank arm length accordingly.

Fourth, to increase the subject pool, the data from the study by Too and Landwer (2000) was combined with the data from the current investigation. This resulted in joint angles measurements from seven crank arm lengths (110, 145, 180, 215, 230, 250, and 265 mm) and greater variability in leg length characteristics. The larger sample size allowed development of regression equations that can be extrapolated to a larger portion of the population. However, with the increased numbers of subjects, there was also greater subject variability, which decreased accuracy of the prediction equation. With the data from both studies combined, two regression equations were determined to be the best predictors of crank arm length when leg length is accounted for. The first equation included total leg length whereas the 2^{nd} equation included both total and lower leg length. The regression equations were:

(1) CAL [mm] = (490 [mm] + 1.423 * (Knee ROM) [deg] – 0.28 * (Tot Leg) [mm] - 1.458 * (Hip Min) [deg]) ± 25[mm]; and
(2) CAL [mm] = (295 [mm] + 1.52 * (Knee ROM) [deg] – 0.25 * (Tot Leg) [mm] - 1.471 * (Hip Min) [deg] + 0.3 * (Low Leg) [mm]) ± 22 [mm] would be reduced to
CAL[mm] = (238 [mm] – 0.25 * (Tot Leg) [mm] + 0.3 * (Low Leg) [mm]) ± 22 [mm].

With the “optimal” knee range of motion (of 72 degrees) and minimum hip angle (of 113 degrees) inserted into the equations, the “optimal” crank arm length to maximize peak power was reduced as follows (with the predicted crank arm length dependent on the leg length):

(1) CAL [mm] = (427 [mm] – 0.28 * (Tot Leg) [mm]) ± 25 [mm]
(2) CAL[mm] = (238 [mm] – 0.25 * (Tot Leg) [mm] + 0.3 * (Low Leg) [mm]) ± 22 [mm]

It should be noted that the standard error in prediction of crank arm length with these equations are 25 and 22 mm, and that the actual "optimal" crank arm length may be different from the predicted one. Although both equations 1 and 2 can be used to predict crank arm length, equation 2 (including the use of both total leg length and lower leg length and having a smaller standard error of prediction) would be the better equation to use.

One final caveat, it should be noted that the focus and results/discussion of this investigation were centered on peak power production in an upright cycling position and not on aerobic performance or in a recumbent position. Therefore, caution must be taken regarding interpretation of the data, and extrapolation of the results to individuals and cycling conditions that are different from those reported in this investigation, since that would be beyond the scope and limitations of this study.

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