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The Effect of Pedal Crank Arm Length and Seat Height on Joint Angles in an Upright Cycling Position

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Abstract

Manipulations in crank arm length and seat height have resulted in significant changes in cycling performance. To better understand how these manipulations affect cycling performance, the purpose of this investigation was to determine the effect of 5 pedal crank arm lengths (110, 145, 180, 215 and 250 mm) and 3 seat height (short, medium, and long) on joint angles (minimum, maximum, and range of motion) of the hip, knee, and ankle, as determined by 3 electrogoniomters in an upright cycling position for17 male participants. Nine 5 x 3 Repeated Measures Factor ANOVAs revealed that 35 mm increments in crank arm length from 110–250 mm resulted in a significant ($p < 0.01$): (1) decrement in the minimum hip and knee angle; (2) increment in the minimum ankle angle; (3) increment in the hip and knee range of motion; and (4) decrement in the ankle range of motion. It was determined that 6 cm changes in seat height from the shortest to the longest seat height resulted in a significant ($p < 0.01$): (1) increment in the minimum and maximum joint angle of the hip, knee, and ankle; and (2) increment in the range of motion of the knee. No significant interactions were found between crank arm length and seat height for different angle measurements (minimum, maximum, and range of motion) of the hip, knee, and ankle. In conjunction with the results of previous investigations, certain joint angle ranges result in more effective cycling performance.

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 [5,14,15], seat height [4,10,12], seat to pedal distance [16], and crankarm length [3,7-9,18]. These manipulations result in changes in lower extremity joint angles (i.e., hip, knee, ankle) that affect cycling performance. For example, an inverted U-curve was reported to best describe the trend in peak power with incrementing crank arm length in an upright position [18] and in a recumbent position [19].

Based on muscle tension-length and force-velocity-power relationships, it can be assumed that any manipulations to lower extremity joint angles 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.

With a systematic change in four seat-tube angles from 25 to 100 degrees, Too [15] reported a decrease in mean hip angle from 114 to 59 degrees (without a change in knee or ankle angle). Seat tube angle was determined by the angle of the bicycle seat tube and a vertical line (perpendicular to the ground) passing through the pedal axle. This systematic change in seat-tube angle resulted in a parabolic curve in power production for a recumbent cycling position where the trunk was kept perpendicular to the ground (with peak power produced at a 76 degree mean hip angle).

Unlike changes in seat-tube angle where only the hip angle is affected, changes in seat-to-pedal distance (or seat height) will affect angles of the hip, knee, and ankle during a pedal cycle. Based on the force-length relationship, a more complex interaction occurs between muscle length and force production when multiple joints and multi-joint muscles that cross the hip/knee and knee/ankle are involved. Changes in seat-to-pedal distance will affect both hip and knee angles, with the effect on the minimum, maximum, and joint angle range on the hip and knee being different. In an upright cycling position with a fixed crank arm length (where the seat-to-pedal distance selected is already at the maximum distance that can be pedaled in), seat height can then only be manipulated to result in a decrease in seat-to-pedal distance. A decrement in seat height (seat-to-pedal distance) will result in a decrement in minimum and maximum hip and knee angles during a pedal cycle, with the joint angle ranges remaining the same. Cycling performance would be maximized with a joint angle range (minimum and maximum hip and knee angles) where contraction of the muscles occur in the most effective portion of the force-length curve (i.e., the portion of the curve that includes resting length). This apparently varies somewhere between 96–100% of trochanteric length for aerobic work and 109% of the medial aspect of the inside leg from the floor to the symphysis pubis for anaerobic work [2,7,12,13]. Because joint angles were not reported in the literature for these investigations, it is unknown as to what hip, knee, and ankle angles will maximize cycling performance in upright cycling positions, or how joint angles will change with different seat height. It can be speculated that if the initial seat height was set at 100% of trochanteric leg length, a systematic decrease in seat height would result in a systematic decrease in the minimum and maximum joint angles of the hip and knee, whereas the joint angle range of motion of the hip and knee would remain the same. On the other hand, if the seat height was increased from 100% trochanteric leg length, it can be speculated that accommodations would have to be made at the ankle, with greater ankle extension during a pedal cycle.

If the crank arm length is free to vary, but the same maximum seat-to-pedal distance is used, then the crank arm length (unlike seat height) can be increased or decreased. However, any changes in crank arm length must then be accompanied by a corresponding but opposite change in seat height if the same seat-to-pedal distance is to be maintained (i.e., if the crank arm length was to be increased, then the seat height must be decreased by the same amount to maintain the same seat-to-pedal distance). With changes in crank arm length, the maximum hip and knee angle in a pedal cycle would also remain the same (with the same seat-to-pedal distance). But, the minimum hip and knee angle would decrease with an increment in crank arm length, while the hip and knee range of motion would increase [19]. The reverse would be true if the crank arm length was to be decreased (i.e., the minimum hip and knee angle would increase, whereas the hip and knee range of motion would decrease). Based on the force-length relationship, this would mean that differences in cycling performance with different crank arm lengths (using the same seat-to-pedal distance) would be attributed to muscle contraction of the hip and knee occurring over a different portion of the force-length curve during a pedal cycle (i.e., greater portion with longer crank arm lengths, and smaller portion with shorter crank arm lengths). This could explain why certain crank arm lengths are more effective than other crank arm lengths in an upright and/or recumbent position.

Currently, it is unknown as to what are the joint angles and how these joint angles are affected with a systematic change in seat-to-pedal distance (seat height) and crank arm length during a pedal cycle. It is also unknown whether there is an interaction between crank arm length and seat height in affecting joint angles. Therefore, the purpose of this study was to determine what joint angles, and how these joint angles change with changes in seat-to-pedal distance (i.e., seat height) and crank arm length. This will include an examination of the minimum and maximum angles, and range of motion of the hip, knee, and ankle during a pedal cycle with a variety of seat heights and crank arm lengths.

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 186 ± 5 cm and 84.7 ± 10.3 kg, respectively. Their total, upper and lower leg lengths were 98.3 ± 3.4, 41.6 ± 2.1, and 56.7 ± 1.9 cm, 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 and three seat heights (see Figure 1).

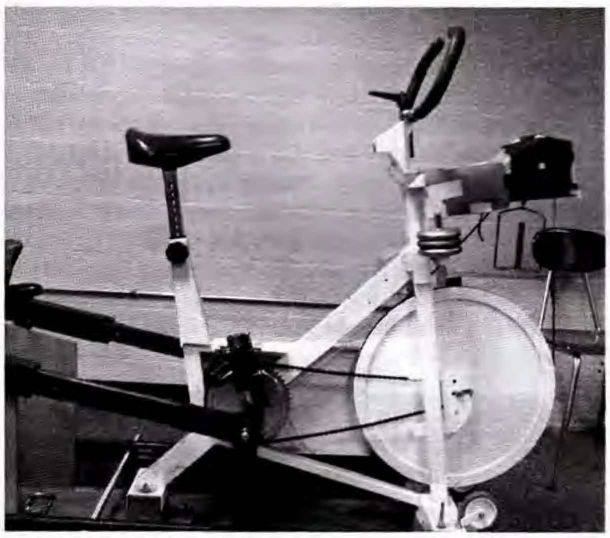

Figure 1. Monark cycle ergometer

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 spindle (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).

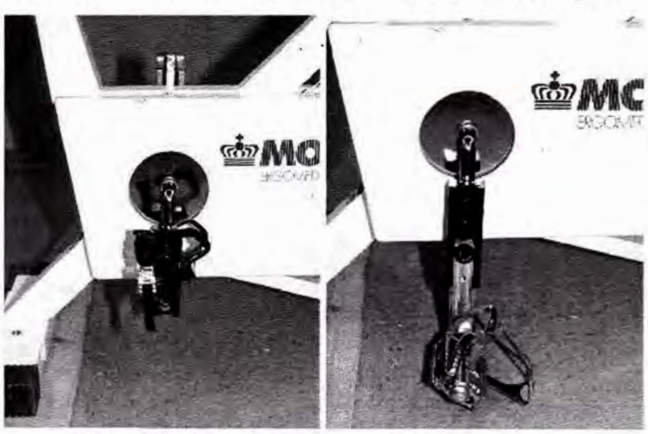

Figure 2. Adjustable pedal shaft mechanism and cranks

The three seat heights 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) were based on each participant's lower extremity length, as measured from the greater trochanter to the floor. The longest seat height was 100% of leg length, whereas the medium and shortest seat height was -6 cm and -12 cm of 100% of leg length, respectively. The large changes in seat height were selected to explore the joint kinematics of what may be considered to be an extreme minimum hip and knee angle during a pedal cycle

Procedures

Two sessions were required of each participant and all procedures were approved by the Institutional Review Board. The first session was used to: (1) explain the research procedures and participant involvement; (2) obtain informed consent and participant characteristics (age, height, mass, leg length); and (3) determine the appropriate seat height settings for the 5 different crank arm lengths. For each participant, the test sequence for the 5 crank arm lengths was randomly determined. For each crank arm length, the test sequence for seat height was randomly determined, and each crank arm length was tested with all 3 seat heights before the next crank arm length was tested. Five crank arm lengths (110, 145, 180, 215, 250 mm) with 3 seat heights (100% of leg length, -6 cm of leg length, -12 cm of leg length) resulted in a total of 15 test conditions.

The second session was use to record joint angles of the hip, knee, and ankle from the right side of the body using 3 electrogoniometers (SG150 and SG100 sensors with a K100 amplifier by Biometrics Ltd). The electrogoniometers were attached to the skin of the trunk, thigh, leg, and foot via double stick tape, and connected to a small 4 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).

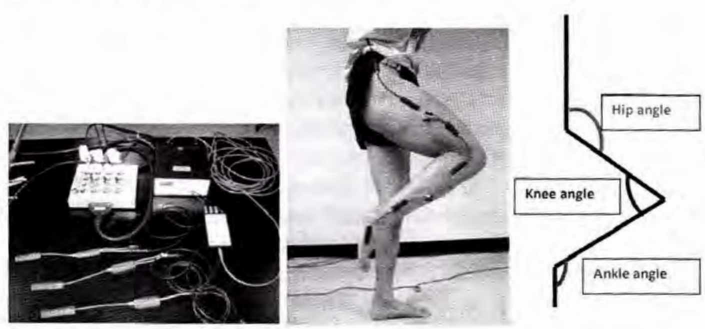

Figure 3. Electrogoniometers

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 1 pedal cycle was completed each second). Once the appropriate cadence was reached (which was generally within a 5–10 second period), a 3 kg mass was applied to the ergometer and data for 10 seconds were recorded (to collect at least 7 complete pedal revolutions). This resulted in a workload of 47.481 joules per pedal revolution or a power output of 47.481 watts for the 10 second data collection period (i.e., 474.81 joules). The participant was then asked to stop pedaling, and the next test condition was set up. There was a minimum of 2 minutes rest between seat height test conditions. After all 3 seat heights for a crank arm length condition were completed, there was a minimum of 4 minutes rest before the next crank arm length condition was 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. 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).

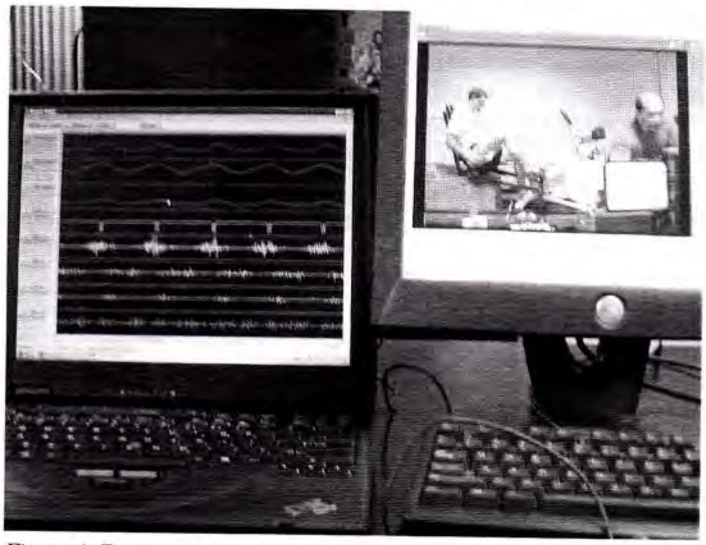

Figure 4. Equipment set-up.

Measurements

Joint angles at the hip, knee, and ankle were recorded by electrogoniometers, 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, with pedal crank arm length and seat height as the independent variables. With five crank arm lengths and three seat height, the statistical analysis was a 5 x 3 Repeated Measures Factor ANOVA. The dependent variable was joint angle. 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. Nine 5 x 3 Repeated Measures Factor ANOVAs were performed using SPSS (IBM SPSS Statistics 19) to determine if there were significant differences ($p < 0.01$) in joint angles with: (1) changes in crank arm length; (2) changes in seat height; and (3) an interaction between crank arm length and seat height. If significant differences were found for the main effects with crank arm length and seat height, post-hoc tests were performed between means (for adjacent crank arm length and seat height) to determine if 35 mm changes in crank arm length and 6 cm changes in seat height resulted in significant differences ($p < 0.05$) in joint angles. Joint angles were plotted to determine trends in joint angles with changes in crank arm length and seat height.

Results

No significant interactions were found with nine 5 x 3 Repeated Measures Factor ANOVAs between pedal crank arm length and seat height for the minimum, maximum angle, and range of motion for the hip, knee, and ankle (which was unexpected). Although there were no significant interactions, there were trends in joint angles with changes in crank arm length and seat height. The following trends 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). No apparent trend was found in the maximum hip, knee, and ankle angle with increasing pedal crank arm length. On the other hand, different trends in joint angles were found with incrementing seat height and include: (1) increasing minimum and maximum hip, knee, and ankle angle; (2) increasing range of motion of the knee (which was unexpected); and (3) no apparent trends in the range of motion for the hip and ankle (see Figures 5–13).

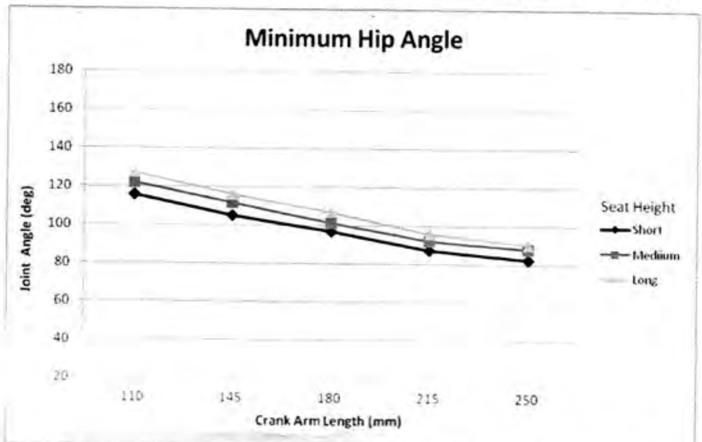

Figure 5. Min hip angle with changes in crank-arm and seat height

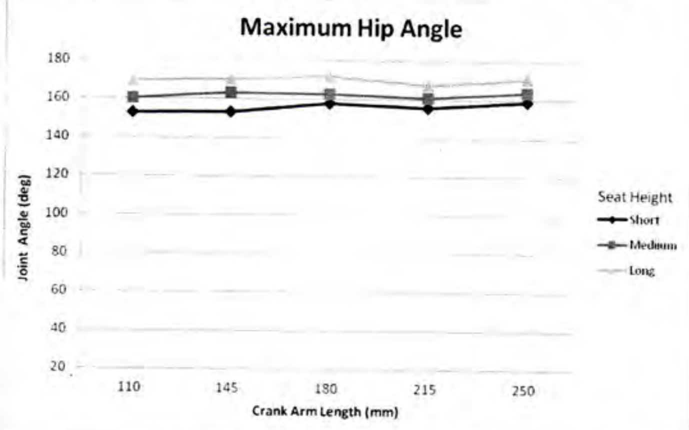

Figure 6. Max hip angle with changes in crank-arm and seat height

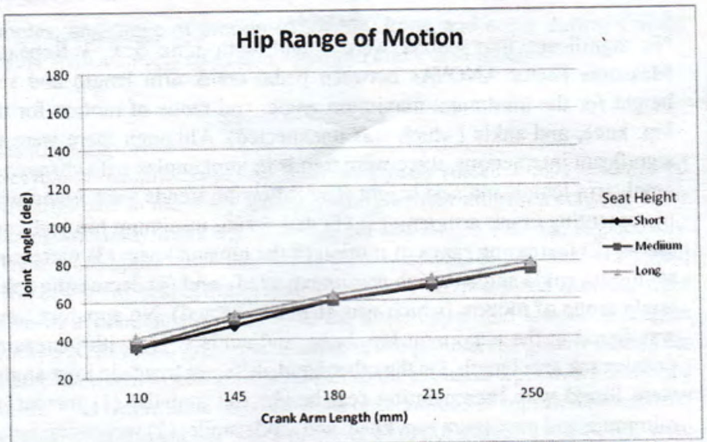

Figure 7. Hip angle Range with changes in crank-arm and seat height

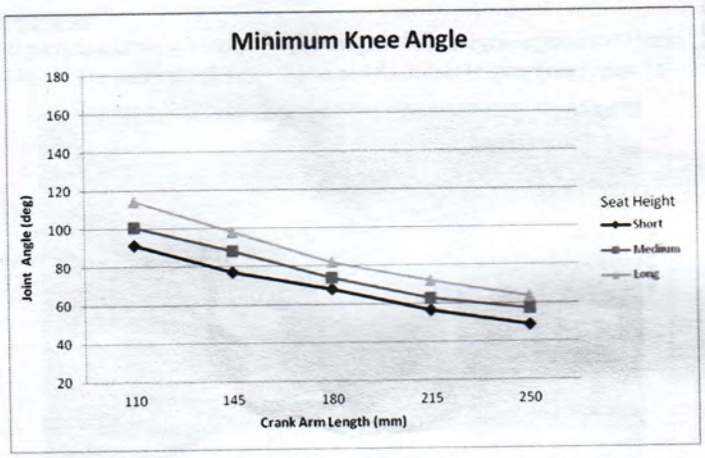

Figure 8. Minimum knee angle with changes in crank-arm and seat height

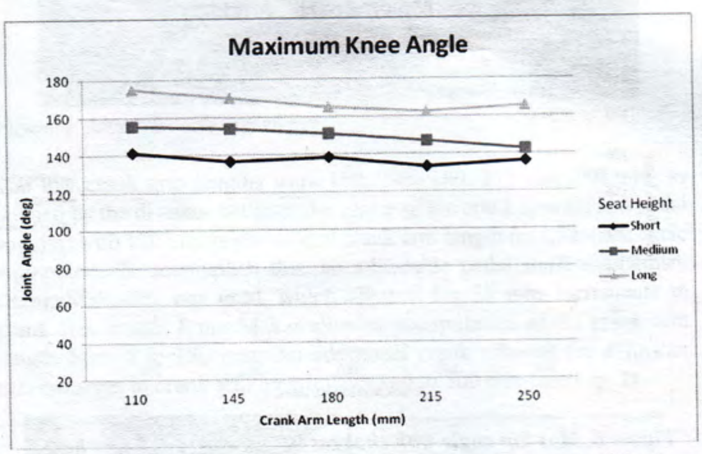

Figure 9. Maximum knee angle with changes in crank-arm and seat height

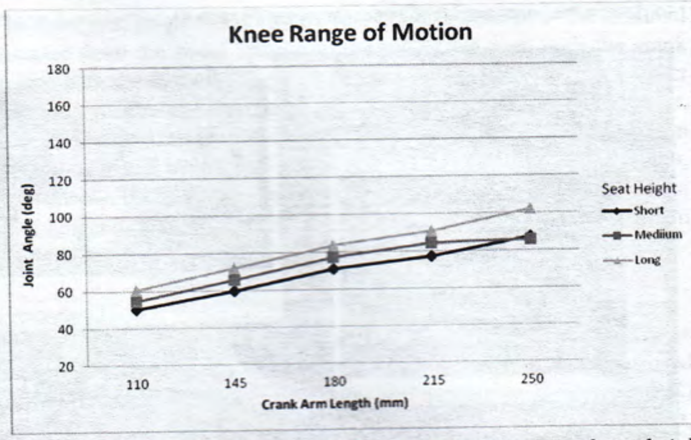

Figure 10. Knee angle Range with changes in crank-arm and seat height

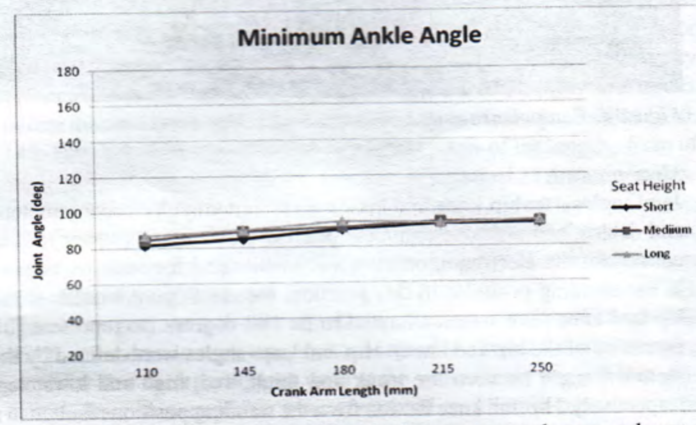

Figure 11. Minimum ankle angle with changes in crank-arm and seat height

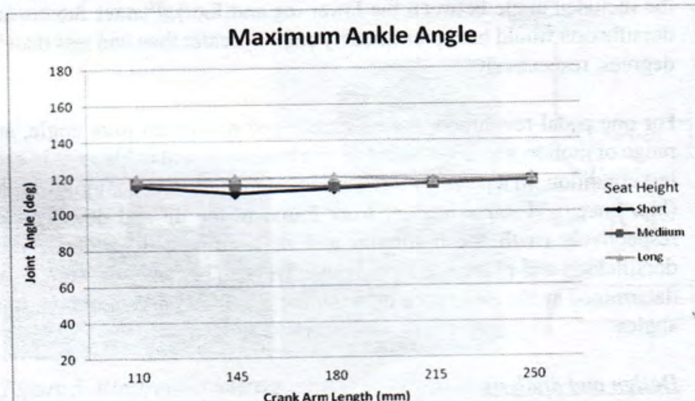

Figure 12. Maximum ankle angle with changes in crank-arm and seat height

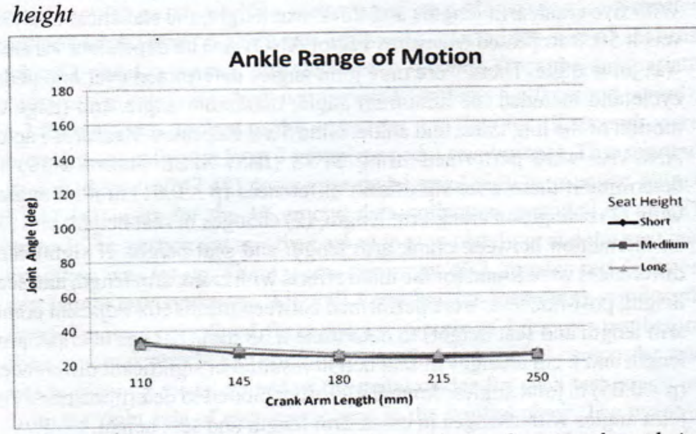

Figure 13. Ankle angle Range with changes in crank-arm and seat height

From Repeated Measures Factor ANOVAs, the main effects for pedal crank arm length and seat height were found to be significant ($p < 0.01$). The **significant main effects for crank** arm length included the minimum angle and range of motion for the hip, knee, and ankle (see Table 1); whereas the **significant main effects for** seat height included the minimum and maximum hip, knee, and ankle angles, along with the range of motion angle of the **knee (see Table 2). (If** the same seat-to-pedal distance [i.e., seat height] was maintained with changes in crank arm length, the maximum joint angle **would not be expected** to be significantly different as the crank arm length changed. Similarly, if the same crank arm length was used with changes **in seat height, the** joint angle range of motion would not be expected to be significantly different).

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
* ($p < 0.01$)

Table 2. Hip, Knee, and Ankle Joint Angles at Three Seat Height (Mean±SE)

	Seat Height		
	Short	Medium	Long
Hip (deg)			
*Min	97.5 ± 5.51	103 ± 4.51	107.4 ± 3.61
*Max	155.8 ± 2.84	162.3 ± 2.22	170.1 ± 2.24
ROM	57.5 ± 3.68	58.6 ± 4.23	61.6 ± 4.48
Knee (deg)			
*Min	68.1 ± 4.86	76.4 ± 4.84	85.9 ± 5.11
*Max	137.1 ± 5.79	149.9 ± 5.77	167.6 ± 3.73
*ROM	68.9 ± 494	73.5 ± 5.18	81.7 ± 6.11
Ankle (deg)			
*Min	88.4 ± 2.24	90.4 ± 2.32	91.7 ± 2.32
*Max	114.9 ± 3.83	116.1 ± 3.5.	119.1 ± 3.07
ROM	26.4 ± 2.94	25.8 ± 3.01	27.4 ± 3.00

Min = Minimum
Max = Maximum
ROM = range of motion
Short = -12 cm of leg length\
Medium = -6 cm of leg length
Long = leg length
* ($p < 0.01$)

For significant main effects in crank arm length, post-hoc tests were use to determine which 35 mm increment in adjacent pedal crank arm length (from 110 mm to 250 mm) resulted in significant changes in joint angles. 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 3). (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).

For significant main effects in seat height, post-hoc tests were use to determine which 6 cm increase in seat height from the shortest seat height to the longest seat height resulted in a significant change in joint angle. For each 6 cm increment in seat height, post-hoc tests revealed a significant ($p < 0.05$): (1) increment in the minimum hip, knee, and ankle angle; (2) increment in the maximum hip and knee angle; and (3) increment in the knee angle range of motion (which was not expected). For the maximum ankle angle, post-hoc tests found only the 6 cm increase from the medium seat height to the longest seat height to result in a significant increase ($p < 0.05$) in the maximum ankle angle (see Table 4).

Table 3. Post-hoc test p-values for significant main effects of crank arm length

	Crank Arm Length (mm) 110 vs. 145	145 vs. 180	180 vs. 215	215 vs. 250
Hip Angle				
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				
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				
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

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

Table 4. Post-hoc test p-values for significant main effects of seat height

	Seat Height: Short vs. Medium	Medium vs. Long
Hip Angle		
Min	0.012	0.010
Max	0.016	0.002
ROM	N/A	N/A
Knee Angle		
Min	0.000	0.002
Max	0.000	0.000
ROM	0.048	0.001
Ankle Angle		
Min	0.001	0.010
Max	0.130	0.004
ROM	N/A	N/A

Min = Minimum
Max = Maximum
ROM = range of motion
Short = -12 cm of leg length\
Medium = -6 cm of leg length
Long = leg length
N/A = not applicable due to non-significant main effect

Discussion

In a pedal cycle, regardless of crank arm length and seat height, the results of this investigation revealed that the minimum and maximum joint angles (of the hip, knee, and ankle) occurs in the up stroke and down stroke, respectively. The minimum and maximum joint angles also increased if the seat height was increased. This is intuitively obvious. However, what is not so intuitively obvious is how the joint angles (absolute and relative angles) change when the crank arm length is systematically increased, and how this relates to cycling performance. 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) and aerobic performance (cycling duration) with increasing crank arm lengths from 110–265 mm (with the 180 mm and 230 mm crank arm length resulting in the largest anaerobic and aerobic cycling performance, respectively) [18,19]. 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).

Crank Arm Length

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 are 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 (41.6 cm) when compared to the lower leg length (56.7 cm) of the participants of 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 when different crank arm lengths are used, 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.

Seat Height

With changes in seat height, similar results were found for the minimum and maximum hip and knee angles, and may also be attributed to the difference between the shorter upper leg length and longer lower leg length. It appears that with a systematic increase in seat height (from the shortest to the longest seat height with 6 cm increments), the minimum hip angle increased from 97.5 to 107.4 degrees (for a change of 9.9 degrees), whereas the maximum hip angle increased from 155.8 to 170.1 degrees (for a change of 14.3 degrees). On the other hand, with the same change in seat height, the minimum knee angle increased from 68.1 degrees to 85.9 degrees (a change of 17.8 degrees), whereas the maximum knee angle increased from 137.1 degrees to 167.6 degrees (a change of 30.5 degrees). This greater change in the maximum knee angle relative to the change in the minimum knee angle (with each successive increment in seat height) apparently resulted in a significantly greater increment in the knee range of motion from the shortest to the longest seat height (and this was unexpected). This would suggest that these different rates and degrees of hip and knee angle changes with incrementing seat height may be attributed to differences between the upper and lower leg length, and a contributing factor affecting cycling performance with changes in seat height. To determine the contribution and activity of various hip and knee joint muscles would again, require the use of EMG to determine when single and multi-joint muscles of the hip and knee are active and inactive during a pedal cycle with different seat heights. This, along with joint angle information from ELGONs and crank position over a pedal cycle with changes in crank arm length would provide a greater understanding of why certain seat heights (in this case, the longest seat height) result in greater cycling performance (when compared to the medium and short one) based on when various muscles may be active over different portions of the tension-length curve to produce force.

Ankle Joint Angles with Changes in Crank Arm Length and Seat Height

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 seat heights and 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 dorsiflexed 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 [17]. (It also appears that as the seat height is systematically increased by 6 cm, from the shortest to the medium to the longest seat height, the minimum ankle angle changed from a dorsiflexed position of 88.4 degrees, to a neutral position of 90.4 degrees, to a greater plantar flexed position of 91.7 degrees, respectively [see Table 2] and may have contributed to the greater cycling performances found with seat heights equal to 100% of leg length or longer).

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.

Implications and Applications

For builders of human powered vehicles (HPVs) in the upright cycling position, the results of this investigation, in conjunction with those of previous investigations [17,18], reveal 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, guidelines will be provided on how to select an appropriate crank arm length.

First, the results of the investigation by Too and Landwer [18] 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. Second, peak power and mean power with repeated measures ANOVAs were found to be significantly different ($p < 0.01$) and greater with the 180 mm crank arm length than with the other crank arm lengths. However, 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. Third, this would suggest that the optimal crank arm length (to optimize joint angles) to maximize anaerobic cycling performance would vary somewhere between 145 mm and 180 mm. However, caution must be taken that the results of the investigation by Too and Landwers [18] may be limited in scope to those with similar leg length characteristics (i.e., total leg length = 93 cm, upper = 40.1 cm, lower = 52.5 cm) as their subjects/participants. Fourth, individuals with different leg length characteristics may need to adjust selection of their crank arm length accordingly. In other words, individuals with substantially shorter total leg lengths (but similar upper and lower leg length ratios) might select a crank arm length closer towards 145 mm than towards 180 mm.

If the preference is for a crank arm length to maximize aerobic cycling performance, Too and Landwer [17] reported the 230 mm crank arm length to result in the longest cycling duration with incrementing workload. With 5 crank arm lengths (110, 145, 180, 230, 265 mm) used in that investigation, Too and Landwer [17] reported an inverted U-shaped curve to best describe cycling duration with increasing crank arm lengths. A repeated measure ANOVA, along with post-hoc tests, revealed that cycling duration was significantly increased ($p < 0.05$) with each increment in crank arm length except from the 180 mm to 230 mm crank arm length. This would suggest that the optimal crank arm length (and joint angles) to maximize aerobic performance would be somewhere between 180 mm and 230 mm. Again, 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 by Too and Landwer [17]. For example, a pedal cadence of 60 rpm (with incrementing workload until the cadence could no longer be maintained) was used by Too and Landwer [17] to determine cycling duration for all crank arm length conditions tested. If a different pedal cadence was to be used (e.g., 128 rpm) by Too and Landwer [17], the optimal crank arm length to maximize cycling duration might no longer have been 230 mm, but may have been shorter (due to an interaction between energy expenditure, power output, pedaling rate [11], and possibly crank arm length). If fact, Barratt, Korff, Elmer, and Martin [1] reported that during maximal cycling, a pedaling rate of 128 rpm is optimal to maximize power for a 150 mm crank arm length. If the same subject characteristics (i.e., total, upper, and lower leg lengths of 94.1, 40.6, and 54 cm, respectively) and cycling conditions were used as those reported by Too and Landwer [17], then it can be assumed that the optimal crank arm length to maximize aerobic cycling performance would vary between 180 mm and 230 mm (and adjustments made towards the 180 mm [or 230 mm] crank arm length, dependent on changes in subject characteristics and cycling conditions).

One final caveat, it should be noted that the focus and results/discussion of this investigation centered on an upright cycling position and not on a recumbent one. Therefore, this information would be treated as such, and more relevant and applicable for human powered vehicles in the upright cycling position.

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With Hand and Foot: HF bikes A new type of bicycle develops...

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Therefore, the tested HF bikes can only be roughly classified here for different applications, HF racing bikes, HF mountain bikes, HF recumbents, HF everyday bicycles, etc. If mainly speed is important for you, test the 4strikebike, the AlEx Amboss, the Dopo bike, the THYS 209 or the Varibike. If you do not want to miss out on terrain, or if you travel a lot in the mountains, you might be happy with the Gildasfire or the Raxibo. If you are planning to make longer tours as an inexperienced rider, you could try the AlEx Amboss, the AlEx Exycle, the Bionic Body Bike, the Exycle, the Raxibo and the Ruderrad. If you like single-speed bicycles, you might like the hanTrieb. Best suited for the heavy traffic in a big city are the AlEx Amboss, the AlEx Exycle, the AlEx Harmony, the Bionic Body Bike, the Exycle, the hanTrieb and the Ruderrad. You should also remember the purpose of HF bikes, which is to allow the use of all muscle groups during cycling. This purpose overrules this differentiation of the existing HF bikes. Due to the distinctive element of the additional hand drive, individual preferences regarding the hand drive and also the respective overall concept are generally more important than the classification of the respective HF bikes. For example, for a rowing movement, try the Moveo, the THYS 209 or the Ruderrad. If you want a movement with normal human alternation, this can best be achieved with the 4strikebike, the Dopo bike and the Raxibo. With the Gildasfire, the hanTrieb, the Tetrad and the Varibike, this is also the case, but you have to find the rhythm yourself—therefore you can interrupt the hand drive at any time.

It is not possible to answer the question of which movement, drive and overall concept best suits in a theoretical article. The bicycles must be ridden. This is all the more true for HF bikes so that you can develop a feeling for the different drive concepts as a rider and individually decide which HF bike best suits your needs. An excellent opportunity to experience the different HF bikes live is each year at the last weekend in April at the special bike fair in Germersheim.

Thanks

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