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DIFFERENCES IN POWER OUTPUT DURING CYCLING AT DIFFERENT SEAT TUBE ANGLES

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SUMMARY

To determine if differences exist in power output during cycling at different seat tube angles (STAs), 12 male, physically active, non-cyclists were analyzed for power output and lower extremity joint kinematics during a 15sec, maximal effort, cycle ergometer test. STA was defined relative to the horizontal and subjects were tested at 69°, 76°, 83° and 90°. All tests were performed on an instrumented, computer interfaced, cycle ergometer, with a modified seat that allowed for variation in the STA. Power output values increased systematically and hip angle decreased systematically, as STA was decreased from 90° to 69°. Other joint kinematic factors remained stable as STA was decreased from 90° to 69°. Based on these results, cycling power output is maximized at shallow STAs and decreased at steeper STAs, within the range of 69° to 90°. The differences in power output may be due to altered muscle lengths and moment arms associated with the changes in hip joint angle.

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INTRODUCTION

The interaction between the cyclist and the bicycle is of primary importance in maximizing cycling performance. This interaction is heavily dependent on the geometric design of the bicycle itself. According to Burke (1994), the angle between the seat tube and the ground is the most important angle on the bicycle frame. In the scientific literature, this angle has commonly been referred to as the seat tube angle (STA) (Gonzalez & Hull, 1989; Heil, Derrick & Whittlesey, 1997; Heil, Wilcox & Quinn, 1995; Price & Donne, 1997; Too, 1991). Despite the importance of this aspect of bicycle geometry, relatively little research has been completed to date on the impact of STA on cycling performance variables.

A few researchers have examined the effect of STA on cardiorespiratory measures during steady-state cycling at angles ranging from 68° to 90°. Generally these researchers have reported that oxygen

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ABBREVIATIONS:
STA seat tube angle

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consumption is increased at more shallow STAs (<76°), and significantly lower at steeper STAs (>76°) (Heil et al, 1997; Heil et al, 1995; Price & Donne, 1997). Despite the fact that oxygen consumption may be increased, road cyclist tend to favor STAs that are less than 76°. To our knowledge, the only experimental report of the effect of STA on short-term maximal power output involved STAs that were representative of a recumbent bicycle (Too, 1991). The STA at which power output was maximized was very shallow, and was far outside the range found on conventional bicycles.

A consistent finding in the above studies was a systematic decrease in the hip angle as STA became more shallow. Other kinematic variables were relatively unchanged at different STAs (Heil et al, 1997; Heil et al, 1995; Price & Donne, 1997; Too, 1991). Most researchers have concluded that the changes in performance are related to musculoskeletal changes stemming from the variation in hip angle (Heil et al, 1997; Heil et al, 1995; Too, 1991), however, Price and Donne (1997) felt that the performance differences were related to changes in the orientation of the foot-pedal interface.

Other research groups have investigated the effects of STA on performance (Browning, Gregor & Broker, 1992; de Groot et al, 1994; Gonzalez & Hull, 1989; Welbergen & Clijsen, 1990), but methodological differences make integration of their results difficult. Browning et al (1992) studied pedal reaction forces and joint moments at three different STAs (conventional, aerodynamic and advanced-aerodynamic). The advanced-aerodynamic position was found to be superior based upon the joint moment integral of the hip, knee and ankle being minimized at that position. Unfortunately, Browning et al (1992) provided no specific information on the actual STAs used. Welbergen and Clijsen (1990) reported that maximal power output and oxygen consumption were maximized in a "standard sitting" position (69° STA) during a 3min supra-maximal cycling test. Welbergen and Clijsen (1990) provided no information about the trunk or hip angles used by the subjects. De Groot et al (1994) measured pedal reaction forces at STAs of 67° and 80°, at a constant external power output of 300W. The investigators reported that resultant sagittal pedal forces and tangential force components peaked approximately 10° earlier in the pedal cycle at the 67° STA. However, the overall force patterns were essentially unchanged over a complete pedal cycle, with the 13° change in STA.

Gonzalez and Hull (1989) used a mathematical model of the cyclist-bicycle system to determine the optimal STA, as well as, optimal values for pedaling cadence, seat height, crank arm length and foot position on the pedal. A moment-based cost function was minimized at a STA of 76°, however, the optimal STA was determined to vary with rider height. Gonzalez and Hull (1989) suggested that the optimal STA was slightly less than 76° for taller riders, and slightly greater than 76° for shorter riders. The researchers concluded that STA should be adjusted to the specific anthropometry of the individual cyclist.

To our knowledge, researchers have not provided evidence of an optimal STA for short-term anaerobic performance, utilizing a conventional frame geometry. The purpose of this study was to determine if differences exist in peak power, mean power, fatigue index and total work, while riding a cycle ergometer at STAs of 69°, 76°, 83° and 90°. In addition, a kinematic investigation was made of mean joint angles for the trunk, hip, knee and ankle, and mean joint range of motion (ROM) for the hip, knee and ankle.

METHODS

Subjects

The participants in the study were 12 healthy, active, male volunteers from the general student population. The mean age of the subjects was 22.4±1.9 years. Average height and mass of the subjects was 1.75±0.06m and 77.9±8.1kg, respectively. Mean upper, lower and total leg lengths were 0.40±0.02m, 0.44±0.02m, and 0.89±0.04m, respectively. Leg length measurements were taken on the right side, using procedures described by Too (1994). Total leg length was measured from the greater trochanter to the ground. Upper leg length was measured from the greater trochanter to the bilateral axis of the knee. Lower leg length was measured from the bilateral axis of the knee to the lateral malleolus. All subjects were physically active, but did not employ cycling in their physical conditioning programs. Four testing sessions were spaced a minimum of two days apart, and subjects were asked to refrain from exercise for 24hr before testing. Informed consent was obtained from all subjects, and the procedures were approved by the Institutional Review Board of Springfield College.

Apparatus

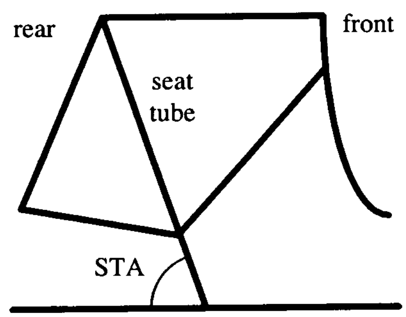
A standard Monark cycle ergometer was instrumented with an electronic load cell in series with the resistance strap and a magnetic reed switch adjacent to the chain ring. Two small magnets were placed 180° apart on the chain ring. The load cell and reed switch were interfaced with a computer according to the method described by Williams, Barnes and Signorile (1988). Data from the load cell and the reed switch were collected utilizing an on-line data collection software package. Complete details regarding the instrumented cycle ergometer and computer interface are provided elsewhere (Williams et al, 1988). The cycle ergometer was also equipped with a racing saddle, toe clips and a specially designed seatpost that allowed adjustments in STA. The instrumented cycle ergometer has been shown to be a highly reliable tool for measuring anaerobic parameters, with test-retest reliability coefficients of 0.91 to 0.97 (Williams et al, 1988).

Limb movements were recorded using standard videography techniques. Images were captured at 60Hz, with a shutter factor of 0.001s. Video recordings were digitized with the Peak Performance Technologies system, and smoothed using a fourth-order zero-lag Butterworth digital filter with a cutoff frequency of 6Hz. Digitized data were used to calculate the mean angles of the trunk, hip, knee and ankle, as well as, the mean joint ROM of the hip, knee and ankle. The video camera used to record movements was placed perpendicular to the right side of the cycle ergometer, at a distance of 5m, to allow images to be captured in the sagittal plane. Small reflective markers were placed over the joint centers of the right shoulder, hip, knee and ankle, and on the right shoe, over the head of the fifth metatarsal. One complete pedal revolution occurring between the fifth and tenth second of the 15sec anaerobic test was evaluated. A qualitative analysis was performed to ensure that the pedal cycle chosen for analysis was representative of the normal pedaling pattern for the subject being evaluated.

Procedures

The subjects were tested according to the 15sec, maximal-effort, anaerobic cycle ergometer protocol described by Williams et al (1988). Subjects rode the instrumented cycle ergometer for 5min at a workload of approximately 50W, as a warm-up. After the warm-up, the subjects stopped momentarily, while an external load of 111.8N was added, yielding a braking resistance that fluctuated between 80.4-82.4N while the subjects pedaled. The load cell allowed the actual resistance to be recorded as the subject pedaled. Upon the signal from the tester, the

FIGURE 1: Convention used to define seat tube angle (STA)



subjects pedaled as fast as possible for 15sec. Subjects were required to remain seated throughout the entire test, and to maintain the same grip on the handle bars. Subjects were allowed to cool down following the anaerobic portion of the test.

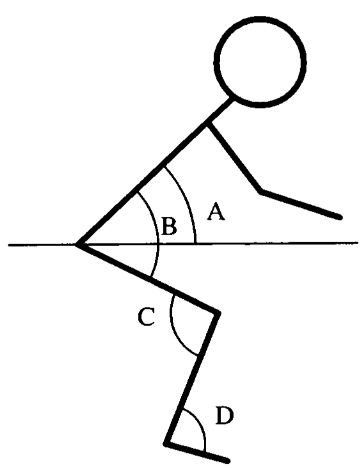
Subjects were tested on four separate occasions, once for each of the different STAs. The STAs used were 69°, 76°, 83° and 90° (from Heil et al, 1995). The convention used to define STA is shown graphically in Figure 1. The order of the four trials was randomly selected without replacement from a list of all possible counterbalanced orders. During the first session subject height and mass were also measured. The cycle ergometer was adjusted so that the seat to pedal distance was 100% of greater trochanter height, the handle bars were at seat height, and the STA was at the appropriate randomly selected angle. At each subsequent STA, seat height, handle bar height in relation to seat height, and seat to handle bar distance were held constant.

Data and Statistical Analysis

Power was calculated as the product of the velocity of the flywheel and the force required to move the flywheel, determined from the magnetic reed switch and the load cell, respectively. Peak power was the single highest power output value for one half pedal revolution. Mean power was the average of the power output values for the entire 15sec test. Peak power and mean power were expressed in watts (W). Fatigue index was the percentage decrease in power output at the end of the test, in relation to the highest power output value achieved during the test. Total work was calculated by integration of power with respect to time, and was expressed in kilojoules (kJ). The mean joint angles were calculated as the average value of the largest angle and smallest angle occurring at a particular joint, during one complete pedal cycle. The joint ROM was calculated by subtracting the smallest joint angle from the largest joint angle occurring at a particular joint, during one complete pedal cycle. A graphic depiction of the convention used to define joint angles is found in Figure 2. All angular measures were expressed in degrees.

A repeated measures design was employed to determine if differences exist in anaerobic performance during a short-duration, maximal-effort, cycle ergometer test at four different STAs. Data were

FIGURE 2: Convention used to define joint angles; A is trunk angle, B is hip angle, C is knee angle, and D is ankle angle



compared using analysis of variance (ANOVA). Each ANOVA was calculated to determine if significant differences existed in the means for one of the dependent variables, between each of the four levels of the independent variable (69°, 76°, 83° and 90° STAs). Newman-Keuls post-hoc multiple comparison test was performed when a significant F ratio was calculated. The statistical procedures were performed using the Statistical Package for the Social Sciences (SPSS) for Windows software package (Norusis, 1993). The alpha level was set at 0.05.

Results

Power Output

The descriptive statistics for the power output variables are presented in Table 1. The mean values for peak power, mean power and total work were all highest at the shallowest STA, and decreased as STA increased. A significant difference ($p<0.05$) was found for the mean peak power output ($F=4.02$), average mean power output

TABLE 1: Means and standard deviations for the power output variables

		seat tube angle			
		69°	76°	83°	90°
peak power (watts)	M	1131.42*	1108.08	1087.42	1048.75
	SD	203.97	213.56	210.98	256.20
mean power (watts)	M	914.75*	896.67*	890.42*	854.92
	SD	130.59	150.72	151.44	181.80
fatigue index (percent)	M	31.17	36.42	30.75	30.50
	SD	8.45	9.23	10.70	11.04
total work (kilojoules)	M	12.40*	12.14*	11.96*	11.44
	SD	1.76	1.97	1.99	2.44

*Mean value differed significantly ($p<0.05$) from value at 90° STA

TABLE 2: Means and standard deviations for the joint angle variables

		seat tube angle			
		69°	76°	83°	90°
trunk angle (degrees)	M	46.42	44.50	45.75	42.42
	SD	6.63	5.28	5.22	4.96
hip angle (degrees)	M	88.75*	92.75**	102.58**	107.67**
	SD	5.48	5.85	7.79	3.77
knee angle (degrees)	M	115.75*	114.25*	116.75*	119.92
	SD	4.69	4.58	5.31	4.85
ankle angle (degrees)	M	119.08	117.00	117.42	119.67
	SD	4.81	7.51	5.52	7.60

*Mean value differed significantly ($p<0.05$) from value at 90° STA
**Mean value differed significantly ($p<0.05$) from other three values

($F=4.97$), and mean total work ($F=6.02$) values, among the four different STAs. Mean peak power was significantly greater ($p<0.05$) at the 69° STA than at the 90° STA. No other significant differences ($p>0.05$) existed among the different STAs for the mean peak power values. The average mean power and mean total work values were significantly greater ($p<0.05$) at the 69°, 76° and 83° STAs than at the 90° STA. No significant differences ($p>0.05$) existed among the 69°, 76° and 83° STAs for the average mean power output or total work values. No significant difference ($p>0.05$, $F=2.08$) was found for the mean fatigue index values among the four different STAs.

Joint Kinematics

The descriptive statistics for the joint kinematic variables are presented in Tables 2 and 3. No significant difference ($p>0.05$, $F=1.93$) was found between mean trunk angle for the four different STAs. Mean hip angle ($F=40.05$) and mean knee angle ($F=7.00$) were significantly different ($p<0.05$) among the four different STAs. The mean hip angles at all the STAs were significantly different ($p<0.05$) from the mean hip

TABLE 3: Means and standard deviations for the range of motion (ROM) variables

		seat tube angle			
		69°	76°	83°	90°
hip ROM (degrees)	M	48.08	47.92	47.92	50.00
	SD	4.40	3.26	3.55	4.88
knee ROM (degrees)	M	79.17	78.00	79.08	80.92
	SD	7.06	6.28	6.02	7.39
ankle ROM (degrees)	M	34.50*	35.92*	41.17**	41.50**
	SD	9.31	9.60	4.82	7.31

*Mean value differed significantly ($p<0.05$) from values at 83° and 90° STA
**Mean value differed significantly ($p<0.05$) from values at 69° and 76° STA

angles at all the other STAs. As STA increased between trials, mean hip angle increased significantly ($p<0.05$). Mean knee angle was significantly greater ($p<0.05$) at the 90° STA than at the remaining STAs. No significant difference ($p>0.05$) existed among the 69°, 76° and 83° STAs for mean knee angle. No significant difference ($p<0.05$, $F=1.15$) was found between mean ankle angle for the four different STAs. No significant difference ($p>0.05$) was found between mean hip ROM ($F=2.58$) or mean knee ROM ($F=1.74$), among the four different STAs. A significant difference ($p<0.05$, $F=5.41$) was found between mean ankle ROM among the four different STAs. Mean ankle ROM was significantly greater ($p<0.05$) at the 83° and 90° STAs than at the 69° and 76° STAs. Mean ankle ROM was not significantly different ($p>0.05$) between the 83° and 90° STAs, or between the 69° and 76° STAs.

Discussion

Power Output

Power output values (peak power, mean power and total work) tended to be greater at more shallow STAs and lower at steeper STAs, in the current investigation. Other researchers have found shallow STAs to be detrimental to steady-state cardiorespiratory performance (Heil et al, 1997; Heil et al, 1995; Price & Donne, 1997). Too (1991), however, found that power output was maximized at a very shallow STA (equivalent to 15° using the current convention), that was well outside the range used in the current study. Too (1991) studied STAs which would be found on recumbent bicycles, whereas, the STAs chosen for the present study represent angles used on conventional bicycles. The industry standard for STAs is 72° to 74°, but cyclists frequently use STAs ranging from 69° to 90° in an effort to find a performance advantage. Such changes in STA can easily be achieved by sliding the seat forward or backward on the rails, or with aftermarket angled seat posts (Burke & Pruitt, 1996).

The mean values for peak power, mean power and total work in the current study ranged from slightly higher than to slightly less than the values reported by other researchers utilizing the same protocol (Cooke, Grandjean & Barnes, 1995; Henrich, Coast & Williams, 1993; Williams et al, 1988). Too (1991, 1994) reported lower mean values for peak and mean power than were found in the current investigation. Aside from the dramatically different STAs examined, the differences are most likely due to differences in the populations tested, or the anaerobic protocols employed. Too (1991, 1994) used a 30sec maximal-effort protocol, whereas, the present researchers used a 15sec maximal-effort protocol. Shorter protocols generally elicit higher power values than longer protocols (Serressee, Simoneau, Boucher & Boulay, 1991).

Heil et al (1995) noted that cyclists usually choose STAs less than or equal to 76°, and speculated that cyclists may do so for reasons other than minimizing oxygen consumption. Cyclists possibly choose shallow STAs to allow for greater power output. Yoshihuku and Herzog (1990) have stated that average power output per pedal cycle is an important factor in cycling performance, and the major determinant of success in sprint cycling. Too (1991) indicated that the maximization of anaerobic power and capacity, which are synonymous with peak power and mean power, might have occurred due to changes in the length of the working muscles, the moment arms of the working muscles, muscle recruitment patterns or joint angles. De Groot et al (1994) have also stated that muscular performance during cycling is dependent on muscle lengths, muscle moment arms and joint angles. Too (1991) did note that the results obtained in the recumbent position were not directly applicable to cyclist riding on a traditional bicycle.

For the present investigation, the total work done over the entire test was calculated by integrating power output measured at the flywheel with respect to time. Power delivered to the pedal in ergometer cycling has been shown to be equivalent to the summed joint powers of the hip, knee, and ankle, minus the rate of change of segmental energy (van Ingen Schenau, van Woensel, Boots, Snackers & de Groot, 1990). Power measured at the flywheel reflects losses in the transmission system and leads to an underestimate of work done at the pedal. The extent of this underestimate had been calculated to be 12.6% (van Ingen Schenau et al, 1990). Due to the comparative nature of the current study this discrepancy was considered inconsequential.

Joint Kinematics

Mean hip angle increased an average of 6.3° with each 7° increase in STA from 69° to 90°. This increase is similar to the increases noted by Heil et al (1995) (5.3°) and Price and Donne (1997) (4°) with similar increments of STA. Too (1991) reported a much larger average increase in hip angle of 18.4°, with 25° increases in STA. The almost complete absence of other lower extremity kinematic changes is consistent with other investigations (Heil et al, 1997; Heil et al, 1995; Price & Donne, 1997; Too, 1991). Changes in performance on the cycle ergometer have been attributed to changes in mean hip angle (de Groot et al, 1994; Heil et al, 1995; Too, 1991; Too, 1994). Differences in hip angle may lead to changes in muscle lengths, muscle moment arms, muscle recruitment patterns and joint angles. Price and Donne (1997), on the other hand, felt that the differences in hip angle were not large enough to explain the differences in cycling performance. Using a mechanical model of the lower extremity, with modified Hill-based muscle parameters, Yoshihuku and Herzog (1990) found that power output was much less sensitive to pelvic inclination changes than to other changes, such as, pedaling cadence. More information regarding the differences in the performance of individual muscles during cycling, with changes in frame geometry is needed before this question can be adequately answered.

Although the STAs studied by Too (1991) were different from those used for the current investigation, there was some overlap in the mean hip angles. The range of hip angles in the present study (88.8° to 107.7°) were only a small portion of the range reported by Too (1991) (58.9° to 114.0°), however, where the two ranges overlapped, the pattern was the same. Power output increased as mean hip angle decreased. Too (1991) noted a reversed trend beyond mean hip angles of 75°, with power output decreasing as mean hip angle decreased. The hip angles in the current study did not overlap with the hip angles reported by Heil et al (1997), Heil et al (1995), or Price and Donne (1997). Not surprisingly, Heil et al (1997) found that oxygen consumption in trained cyclist was lowest at the hip angle subjects rode at on their own bicycles. Non-cyclists were used in the current investigation to control for this potentially confounding, training-related effect.

Conclusions

In the present study, power output increased as STA and mean hip angle decreased, in the presence of minimal other kinematic changes. Changes in mean hip angle would lead to changes in the functional length of the muscles involved during the pedal cycle. Muscle length, force and contraction velocity combine in a complex, three dimensional relationship (Lieber, 1992), which ultimately determines mechanical muscular performance. Based on the nature of the complex relationships between force, length and contraction velocity, along with the results of experimental and analytical studies, the muscle force-length-velocity interaction is a variable that should be able to be optimized (de Groot et al, 1994). Future research should be directed at determining how this complex variable is optimized during cycling at different STAs. Specifically, the interaction of different STAs and pedaling cadences should be investigated experimentally.

When examining the effects of STA and cadence variation, the researcher must also control seat height, crank length and foot position on the pedal. Gonzalez and Hull (1989) have examined these five variables analytically, and have determined that there is an interaction among the five factors. Altering STA may also affect aerodynamic factors which could influence performance.

The standard recommendation for cyclists regarding STA, has been to select an angle that will result in the knee of the forward leg being over the pedal spindle when the cranks are horizontal (Burke & Pruitt, 1996). The rationale for this recommendation is not abundantly clear, but it may be that this position provides for even weight distribution. If this recommendation is followed, then STÅ becomes dependent on femur length. A longer femur would require a more shallow STA, and a shorter femur would necessitate a steeper STA. Indeed, Gonzalez and Hull (1989) found that the mathematically derived optimal STAs for taller cyclists and shorter cyclists were respectively more shallow and steeper than for average cyclists, at a constant 200W power output. In the present study there was no association between femur length, and the STA at which power output was maximized. In other words, the subjects with the longest and shortest thighs, did not achieve peak power output at more shallow and steeper STAs than the other subjects.

In conclusion, power output values while cycling at different STAs tended to be higher at more shallow STAs, and lower at steeper STAs. The changes in power output were accompanied by changes in mean hip angle, which presumably could affect working muscle lengths, muscle moment arms and muscle recruitment patterns. All possible STAs between 69° and 90° were not tested, therefore STA was not truly optimized for power output. However, based on the evidence at hand, STA is a variable that could potentially be optimized for each cyclist. Further research is needed before the factors leading to changes in cycling performance while cycling at different STAs can be completely understood. Researchers also need to be cognizant of the potential interaction of many variables when designing cycling related studies.

References

Browning, R. C., Gregor, R. J. and Broker, J. P. (1992).
Lower extremity kinetics of elite athletes in aerodynamic cycling positions.
Medicine and Science in Sports and Exercise, ***24:*** *S186.*

Burke, E.R. (1994).
Proper fit of the bicycle.
In Clinics in sports medicine: Bicycling injuries.
W. B. Saunders, (Edited by M.B. Mellion and E.R. Burke), Philadelphia, PA., pp. 1-14.

BURKE, E. R. AND PRUITT, A. L. (1996).
Body positioning for cycling.
In High tech cycling.
Human Kinetics, (Edited by E.R. Burke), Champaign, IL., pp. 79-99.

COOKE, W. H., GRANDJEAN, P. W. AND BARNES, W. S. (1995).
Effect of oral creatine supplementation on power output and fatigue during bicycle ergometry.
*Journal of Applied Physiology, **78**: 670-673.*

DE GROOT, G., WELBERGEN, E., CLIJSEN, L., CLARIJS, J., CABRI, J. AND ANTONIS, J. (1994).
Power, muscular work, and external forces in cycling.
*Ergonomics, **37**: 31-42.*

GONZALEZ, H. AND HULL, M. L. (1989).
Multivariable optimization of cycling biomechanics.
*Journal of Biomechanics, **22**: 1151-1161.*

HEIL, D. P., DERRICK, T. R. AND WHITTLESEY, S. (1997).
The relationship between preferred and optimal positioning during submaximal cycle ergometry.
*European Journal of Applied Physiology, **75**: 160-165.*

HEIL, D. P., WILCOX, A. R. AND QUINN, C. M. (1995).
Cardiorespiratory responses to seat-tube angle variation during steady-state cycling.
*Medicine and Science in Sports and Exercise, **27**: 730-735.*

HENRICH, T. W., COAST, J. R. AND WILLIAMS, J. H. (1993).
The effect of circulatory occlusion on short term bicycle ergometer power output.
*Journal of Human Movement Studies, **25**: 233-241.*

LIEBER, R. L. (1992).
Skeletal muscle structure and function.
Williams and Wilkins, Baltimore, MD., pp. 54-63.

NORUSIS, M. J. (1993).
SPSS For Windows: Advanced statistics release 6.0.
SPSS, Chicago, IL.

PRICE, D. AND DONNE, B. (1997).
Effect of variation in seat tube angle at different seat heights on submaximal cycling performance in man.
*Journal of Sports Sciences, **15**: 395-402.*

SERRESSE, O., SIMONEAU, J. A., BOUCHARD, C. AND BOULAY, M. R. (1991).
Aerobic and anaerobic energy contribution during maximal work output in 90s determined with various ergocycle workloads.
*International Journal of Sports Medicine, **12**: 543-547.*

Too, D. (1991).
The effect of hip position/configuration on anaerobic power and capacity in cycling.
International Journal of Sport Biomechanics, 7: 359-370.

Too, D. (1994).
The effect of trunk angle on power production in cycling.
*Research Quarterly For Exercise and Sport, **65**: 308-315.*

van Ingen Schenau, G. J., van Woensel, W. W. L. M., Boots, P. J. M., Snackers, R. W. and de Groot, G. (1990).
Determination and interpretation of mechanical power in human movement: application to ergometer cycling.
*European Journal of Applied Physiology, **61**: 11-19.*

Welbergen, E. and Clijsen, L. P. V. M. (1990).
The influence of body positioning on maximal performance in cycling.
*European Journal of Applied Physiology, **61**: 138-142.*

Williams, J. H., Barnes, W. S. and Signorile, J. F. (1988).
A constant-load ergometer for measuring peak power output and fatigue.
*Journal of Applied Physiology, **65**: 2343-2348.*

Yoshihuku, Y. and Herzog, W. (1990).
Optimal design parameters of the bicycle-rider system for maximal muscle power output.
*Journal of Biomechanics, **23**: 1069-1079.*

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